Co-ordinated Design of PSS and TCSC Damping Controllers in Multi-machine Power System using PSO

A Thesis Submitted in Partial Fulfilment
Of the Requirements for the Award of the Degree of

MASTER OF TECHNOLOGY

in

Electrical Engineering

(Power Control & Drives)

by

SUNKARA SUNIL KUMAR

Roll No: 211EE2132

Department of Electrical Engineering
National Institute of Technology Rourkela
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Under the Supervision of

Prof. Prafulla Chandra Panda

Department of Electrical Engineering

National Institute of Technology Rourkela

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Dedicated

To

My beloved Parents

DEPARTMENT OF ELECTRICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

ORISSA, INDIA-769008

CERTIFICATE

This is to certify that the thesis entitled "**Co-ordinated Design of PSS and TCSC Damping Controllers in Multi-Machine Power System using Particle Swarm Optimization"**, submitted by **Mr. Sunkara Sunil Kumar** in partial fulfillment of the requirements for the award of **Master of Technology in Electrical Engineering** with specialization in "**Power Control and Drives**" at National Institute of Technology, Rourkela. A Bona fide record of research work carried out by him under my supervision and guidance. The candidate has fulfilled all the prescribed requirements. The Thesis which is based on candidates own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a master of technology degree in Electrical Engineering.

Place: Rourkela

Date:

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SUNKARA SUNIL KUMAR

CONTENTS

ABSTRACT

Transmission networks of modern power systems are becoming increasingly stressed because of growing demand and restrictions on building new lines. One of the consequences of such a stressed system is the threat of losing stability following a disturbance. Transient stability improvement is essential for maintaining system security that is the incidence of a fault should not lead to tripping of generating unit due to loss of synchronism. Flexible ac transmission system (FACTS) devices are found to be every effective in stressing a transmission network for better utilization of its existing facilities without sacrificing the desired stability margin. Amongst the available FACTS devices for transient stability enhancement, the TCSC is the most versatile one and it is a series FACTS device which allows rapid and continuous changes of the transmission line impedance. It has great application and potential in accurately regulating the power flow on a transmission line, damping inter-area power oscillations, mitigating the sub-synchronous resonance and improving the transient stability.

Power System Stabilizer (PSS) is installed in Automatic Voltage Regulator (AVR) detects changes in the generator output power and by controlling the excitation value it reduces the power swings in the system.PSS cannot provide sufficient damping for inter-area oscillations in the Multi-machine power system. We can overcome this problem by providing proper Co-ordination of PSS and TCSC using an optimization technique in multi machine power system.Here, we used particle swarm optimization as an optimization technique for Co-ordination of PSS and TCSC damping controllers. The transient stability improvement of the single machine infinite bus system (SMIB) and three machines, nine bus power system at different loading conditions is investigated in this work.

This Report presents coordinated control tuning of power system stabilizer (PSS) with thyristor controlled series capacitor (TCSC). The design of proposed coordinated damping controller is formulated as an optimization problem and the controller gains are optimized instantaneously using particle swarm optimization (PSO). Here single machine infinite bus system and the multi-machine power system employed with PSS and TCSC is considered. The coordinated tuning among the damping controllers is performed on the non-linear power system dynamic model. Finally, the proposed coordinated controller performance is discussed with time domain simulations. Different loading conditions are employed on the test system to test the robustness of proposed coordinate controller and the simulation results are compared with four different control schemes.

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CHAPTER 1
INTRODUCTION

1.1 Overview:

Electric energy is an essential ingredient for the industrial and all round development of any country. It is a coveted form of energy, because it can be generated centrally in bulk and transmitted economically over long distances. Further, for domestic and industrial applications it can be adapted easily and efficiently. The per capita consumption of electrical energy is a reliable indicator of a country's state of development. The basic structure of a power system is as shown in Fig.1.1.and the main components of electric power system are Generating stations, transmission lines and the distribution systems. Generating stations and a distribution systems are connected through transmission lines, which is also connect one power system (grid, area) to another. A distribution system connects all the loads in a particular area to the transmission lines.

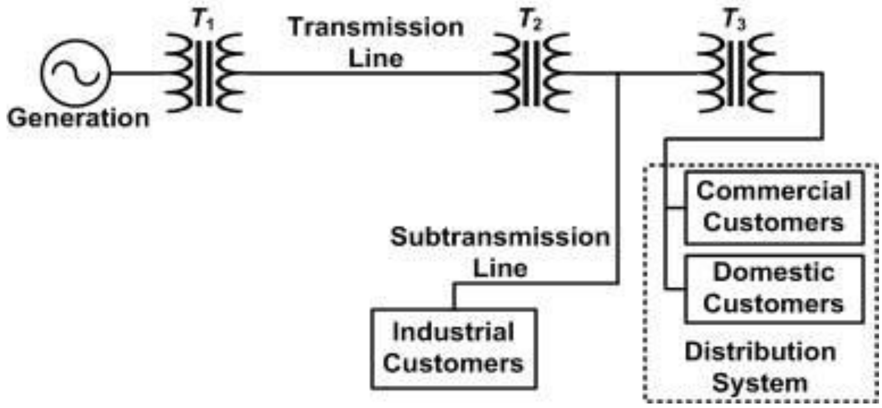


Fig. 1.1 power system basic structure

Modern power systems are designed to operate efficiently to supply power on demand to various load centres with high reliability [1]. The generating stations are often located at distant locations for economic, environmental and safety reasons. In addition to transmission lines that carry power from the sources to loads, modern power systems are also highly interconnected for economic reasons.

The benefits of interconnected system are:

i. Exploiting load diversity
ii. Sharing of generation reserves
iii. Economy gained from the use of large efficient units without sacrificing reliability.

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited [1] due to limited resources and environmental restrictions. Now, more than ever, advanced technologies are vital for the reliable and secure operation of power systems. To attain both operational reliability and financial profitability, it has become clear that more efficient utilization and control of the *existing* transmission system infrastructure is required. Better utilization of the existing power system is provided through the application of advanced control technologies recent development of power electronics introduces the employ of FACTS controllers in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be oppressed to improve the voltage stability, and steady state and transient stabilities of a complex power system [2]. This allows increased utilization of existing network closer to its thermal loading capacity, and thus avoiding the need to construct new transmission lines. The well known FACTS devices are namely SVC, STATCOM, TCSC, SSSC and UPFC.

Electromechanical oscillations in power systems are a problem that has been challenging engineers for years. These oscillations may be very inadequately damped in some cases, resulting in mechanical weariness at the machines and undesirable power variations across the important transmission lines. For this reason, the applications of the controllers to provide better damping for these oscillations are of utmost importance. With increasing transmission line loading over long distances, the application of PSSs might in some cases, not provide adequate damping for the inter-area power swings in a multi-machine system. In these cases, other efficient solutions are needed to be studied. Flexible AC transmission systems devices are one of the recent propositions to assuage such situations by controlling the power flow along the transmission lines and improving power oscillations damping. The use of these controllers increases the flexibility of the operation by providing more options to the power system operators. Amongst the available FACTS [3] devices for transient stability enhancement, the TCSC is the most versatile one. The TCSC is a series FACTS device which allows rapid and continuous changes of the transmission line impedance. It has great application and potential in accurately regulating the power flow on a transmission line, damping inter-area power oscillations, mitigating the sub-synchronous resonance and improving the transient stability.

In the steady state, FACTS controllers like TCSC, help in controlling and increasing the power flow through a line. However, [2] the other important aspects of these controllers are their ability to be used during the large disturbances like faults to improve the transient stability of a power system. A traditional lead-lag damping controller structure is preferred by the power system utilities because of the ease of on-line tuning and also lack of assurance of the stability by some adaptive or variable structure methods. On the other hand, it was shown that the appropriate selection of the conventional lead-lag controller parameters results in effective damping to low frequency electromechanical oscillations. Unfortunately, the problem of the conventional lead-lag POD controller design is a multimodal optimization problem (i.e., there exists more than one local optimum).Hence, the conventional optimization techniques are not suitable for such a problem. Thus, it is required that the heuristic methods, which are widely used for the global optimization problems are developed.

The interaction among stabilizers may increase or degrade the damping of the particular modes of rotor oscillation. This problem may occur especially after the clearance of a critical fault, if FACTS [3] devices are applied in the same area. Interactions between damping controllers can adversely influence the rotor damping of generators and under weakly interconnected system conditions it can even cause dynamic instability and restrict the operating power range of the generators. To improve the overall system performance, many researches were made on the coordination between PSSs and FACTS damping controllers. Some of these methods are based on the complex nonlinear simulation, while the others are based on the linearized power system model. However, linear methods cannot properly capture the complex dynamics of the system, especially during the critical faults. This develops difficulties for tuning the TCSC damping controller and PSS in that the controllers tuned to provide the desired performance at a small signal condition do not guarantee acceptable performances in the event of large disturbances [3].

1.2 Literature Review:

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. However, recent studies reveal that FACTS controllers could be employed to enhance power system stability in addition to their main function of power flow control. The literature shows an increasing interest in this subject for the last two decades, where the enhancement of system stability using FACTS [2] controllers has been extensively investigated. This work presents a comprehensive review on the research and developments in the power system stability enhancement using FACTS damping controllers. The drive towards deregulated environment may result in simultaneous installation of different FACTS controllers in power system. These multiple FACTS controllers have the potential to interact with each other. This interaction may either deteriorate or enhance system stability depending upon the chosen controls and placement of FACTS controllers. Hence there is a need to study the interaction between the FACTS controllers.

The various interactions can potentially occur between the different FACTS controllers, as well as between FACTS controllers and Power System Stabilizers (PSS) [1] in a multi machine power system environment. These likely interactions have been classified into different frequency ranges and various interaction problems between FACTS controllers or FACTS to PSS's from voltage stability/ small signal stability view point are presented. The PSS is a device that improves the damping of generator electromechanical oscillations. Stabilizers have been employed on large generators for several decades, permitting utilities to improve stability-constrained operating limits. In order to describe the application of the PSS, it is necessary to introduce general concepts of power-system stability and synchronous generator operation. An explanation regarding small-signal stability, high-impedance transmission lines, line loading, and high-gain fast-acting excitation systems is provided. Transient stability is discussed, including synchronizing and damping torques. The power-angle curve is used to illustrate how fault-clearing time and high initial response excitation systems can affect transient stability. The term "power-system stability" has become increasingly popular in generation and transmission. The sudden requirement for power-system stabilizers [1] (PSSs) has created confusion about their applicability, purpose, and benefit to the system. This work discusses the fundamentals of the PSS and its effectiveness.

Transient stability [2] is important from the view point of maintaining system security that is the incidence of a fault should not lead to tripping of generating unit due to loss of synchronism and the possibility of a cascaded outage leading to system black out. TCSC allows the fundamental capacitive reactance to be smoothly controlled over a wide range. The TCSC controller can be designed to control the power flow, to increase the transfer limits or to improve the transient stability. The TCSC controller can provide a very fast action to increase the synchronization power through quick changing of the equivalent capacitive reactance to the full compensation in the first few cycles after a fault, hence subsequent oscillations are damped. It has been observed that TCSC controller can improve the stability margin significantly. TCSC controller provides variable impedance, which is required for the compensation. In the present work PSS and TCSC [2] damping controllers are designed for single machine infinite bus (SMIB) and multi machine power system using particle swarm optimization (PSO) technique with MATLAB programming. Multi-machine power system with turbine and governing system is modeled.Modeling is done for system with PSS and TCSC controllers. Effect of PSS and TCSC damping controller parameters variation on rotor angle and on rotor speed is also studied. A detailed analysis is conducted for the proposed controller for different control schemes.

Particle Swarm Optimization (PSO) algorithm appeared as a promising algorithm for handling the optimization problems.PSO shares many similarities with GA optimization technique, like initialization of population of random solutions and search for the optimal by updating generations. One of the most promising advantages of PSO over GA is its algorithmic simplicity as it uses a few parameters and easy to implement. In PSO, the potential solutions, called particle, fly through the problem space by following the current optimum particles. a PSO algorithm has been suggested for coordinated design of a TCSC controller and PSS in power systems for enhancing the power system stability. The design problem of PSS and TCSC based controllers is formulated as a time domain based optimization problem. PSO algorithm is employed to search for optimal controller parameters, by minimizing the time domain based objective function, in which the deviation in the oscillatory rotor speed of the generator is involved.

1.3 Objectives and Scope of the Project:

The objectives of the project are:

- To carry out damping of inter-area oscillations in multi machine power system.
- To enhance the transient stability of power system.
- To enhance the dynamic stability of power system.

1.4 Organization of the Thesis:

This thesis is organized into 7 chapters:

Chapter 1

Gives an outline of the thesis, reviews the range of published material on the objective of the work and determines the objectives and scope of the project.

Chapter 2

This chapter discusses brief introduction about FACTS, different types of FACTS Controllers and its importance and power system stability and transient stability and factors influencing transient stability.

Chapter 3

This chapter gives Modelling of Single Machine Infinite Bus System with Exciter and TCSC damping controllers. Modelling of SMIB system and modelling of PSS and TCSC and TCSC operation. Modelling of TCSC .

Chapter 4

This chapter presents Co-ordinated Design of PSS and TCSC Damping Controllers In Single Machine Infinite Bus System using PSO. Here we discuss Particle Swarm Optimization and Simultaneous Coordinated Design of SMIB with PSS and TCSC using PSO.

Chapter 5

This chapter gives Co-ordinated Design of PSS and TCSC Damping Controllers in Multi-machine power system using PSO.Here we discuss Power flow solution by Newton Raphson Method and dynamic modelling of three machine nine bus system and its coordination using Particle Swarm Optimization.

Chapter 6

This chapter presents simulation results of the single machine infinite bus system during fault condition with PSS and TCSC controller with and without coordination using PSO and also three machine nine bus system with three phase fault condition with PSS and TCSC controller coordination using PSO and discusses in details.

Chapter 7

This chapter concludes the thesis and discusses the future scope of the work.

CHAPTER 2

FACTS CONTROLLERS

The IEEE Power Engineering Society (PES) Task Force of the FACTS Working Group has defined FACTS and FACTS Controller as given below [3].

2.1 Flexible Alternating Current Transmission Systems (FACTS):

In its most general expression, the FACTS concept is based on the substantial incorporation of power electronic devices and methods into the high-voltage side of the network, to make it electronically controllable and to increase power transfer capability. Several kinds of FACTS [2] controllers have been commissioned in various parts of the world. The most popular are: Tap changers of load, phase-angle regulators, static VAR compensators, thyristor-controlled series compensators, inter phase power controllers, static compensators, and unified power flow controllers.

2.2 Transmission System Inherent Limitations:

The characteristics of a given power system evolve with time, as load grows and generation is added. If the transmission facilities are not upgraded sufficiently the power system becomes vulnerable to steady-state and transient stability problems, as stability margins become narrower. The ability of the transmission system to transmit power becomes impaired by one or more of the following steady-state and dynamic limitations[4]:

- Angular Stability;
- Voltage Magnitude;
- Thermal Limits;
- Transient Stability;
- Dynamic Stability.

These limits define the maximum electrical power to be transmitted without causing damage to transmission lines and electric equipment. In principle, limitations on power transfer can always be relieved by the addition of new transmission and generation facilities. Alternatively, FACTS controllers can enable the same objectives to be met with no major alterations to system layout.

2.3 Benefits of FACTS Controllers:

- Power flow can be controlled.
- The loading capacity of lines is increased up to their thermal capabilities.
- Increase the system security though raising the transient stability limit, limiting short circuit currents and overloads, managing cascading blackouts and Damping electromechanical oscillations of lower systems and machines.
- For setting new generation it will provide greater flexibility.
- Transmission lines are upgraded.
- It will reduce reactive power flows, because of this lines can carry more active power.
- It will provide secure tie line connections to neighbouring utilities and regions thereby decreasing overall generation reserve requirements on both sides.
- Loop flows are reduced.
- The utility of lowest cost generation is increased.

2.4 Basic Types of FACTS Controllers:

FACTS Controller is power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters.

It is worthwhile to note the words "other static Controllers" in this definition of FACTS ensure that there can be other static Controllers which are not based on power electronics. The general symbol for FACTS Controller is shown in Fig. 2.1(a). FACTS Controllers are divided into four categories [3]:

i) Series FACTS Controllers

ii) Shunt FACTS Controllers

iii) Combined Series-Series FACTS Controllers

iv) Combined Series-Shunt FACTS Controllers

(i) Series FACTS Controllers:

These FACTS Controllers could be variable impedance such as capacitor, reactor or a power electronic based variable source, which in principle injects voltage in series with the line as illustrated in Fig. 2.1(b). As long as the voltage is in phase quadrature with the line current, the series Controllers only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

(ii) Shunt FACTS Controllers:

The shunt Controllers may be variable impedance such as capacitor, reactor or power electronic based variable source, which is shunt connected to the line in order to inject variable current, as shown in Fig. 2.1(c). As long as the injected current is in phase quadrature with the line voltage, the shunt Controllers only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

(iii) Combined Series-Series FACTS Controllers:

These Controllers are the combination of separate Series FACTS Controllers, which are controlled in a coordinated manner in a multiline transmission system, as illustrated in Fig. 2.1(d). This configuration provides independent series reactive power compensation for each line but also transfers real power among the lines via power link. The presence of power link between series controllers names this configuration as “Unified Series-Series Controller”.

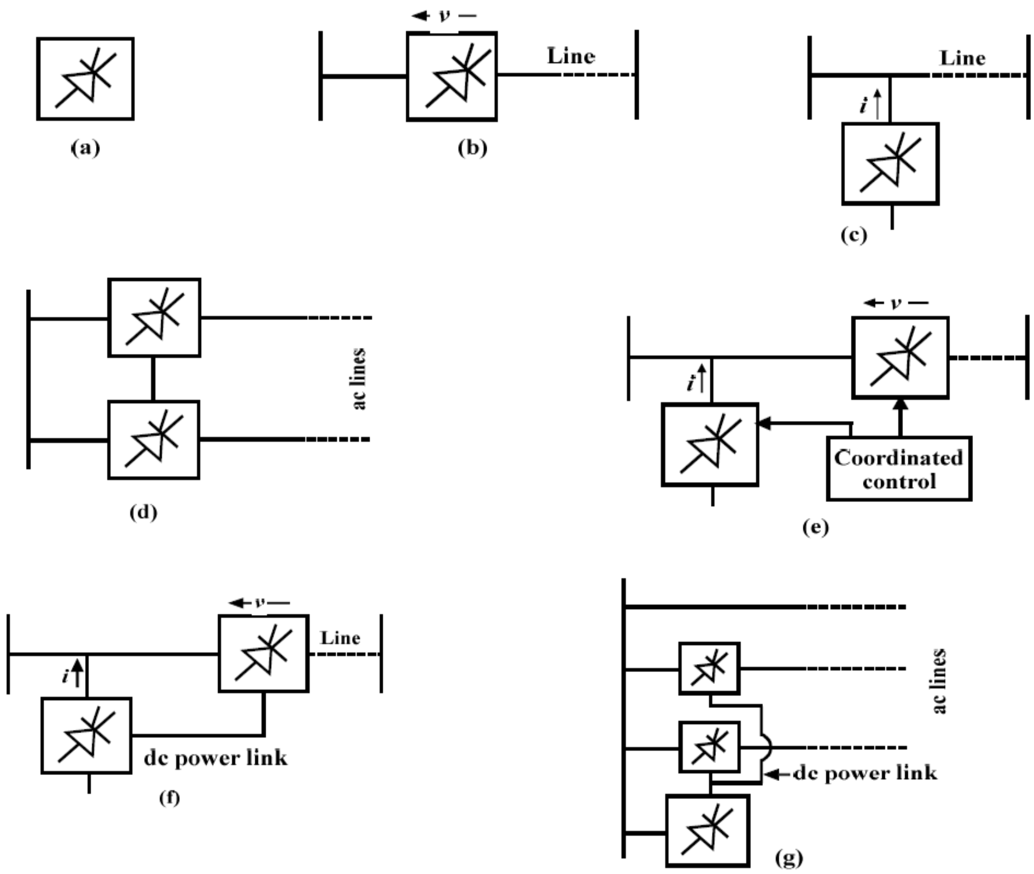


Fig. 2.1 Basic Types of FACTS Controllers [3]: (a) general symbol for FACTS Controller, (b) Series FACTS Controller, (c) Shunt FACTS Controller, (d) Unified series-series FACTS Controller, (e) Coordinated series and shunt Controller, (f) Unified series-shunt Controller (g) Unified Controller for multiple lines

(iv) Combined Series-Shunt FACTS Controllers:

These are combination of separate shunt and series controller, which are controlled in a co-ordinated manner (Fig. 2.1(e)) or a Unified Power Flow Controller with series and shunt elements (Fig. 2.1(f)). When the Shunt and Series FACTS Controllers are unified; there can be a real power exchange between the series and shunt controllers via power link.

2.5 Static Shunt Compensators [3]: SVC and STATCOM

Although static shunt compensators in both transmission systems and distribution systems have the same structure, their objectives are different due to their concerns on the power quality issues.

The primary objectives of a shunt compensator in a distribution system are as follows

- Compensation of poor load power factor so that the current drawn from the source will have a nearly unity power factor.
- Suppression of harmonics in loads so that the current drawn from source is nearly sinusoidal.
- Voltage regulation for the loads that cause fluctuations in the supply voltage.
- Cancelation of the effect of unbalance loads so that the current drawn from the source is balanced (load balancing).

All of these objectives are not necessarily met for a typical shunt compensator. The required shunt compensator should be designed in view of the needs of load to be compensated since each of these functions has a certain cost to the compensator.

On the other hand, the objectives of these shunt compensator in a transmission system are as given below in order to increase the transmitted power in the transmission lines.

- Midpoint voltage regulation for Line Segmentation in order to increase transmittable power in the transmission system.
- End of line voltage support to prevent voltage instability requires the compensation of load having poor factor. This increases the maximum power transmission capability of the transmission line while improving the voltage instability limits.
- Improvement of transient stability margin by increasing the maximum transmittable power in the transmission line.
- Power oscillation damping by exchanging active (real) power with power system
- so that oscillations in the machine angle due to any minor disturbance can be damped out rapidly.

2.5.1 Static Var Compensator (SVC)

According to definition of IEEE PES Task Force of FACTS Working Group:

A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).This is a general term for a Thyristor Controlled Reactor (TCR) or Thyristor Switched Reactor (TSR)[2] and/or Thyristor Switched Capacitor (TSC) (Fig. 1.3). The term, "SVC" has been used for shunt connected compensators, which are based on thyristors without gate turn-off capability. It includes separate equipment for leading and lagging vars; the thyristor –controlled or thyristor – switched reactor for absorbing reactive power and thyristor – switched capacitor for supplying the reactive power [3].

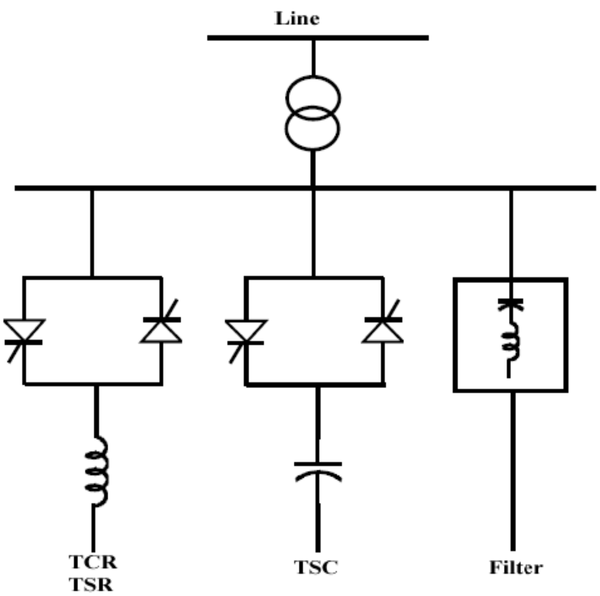


Fig. 2.2 Static Var Compensators: Thyristor Controlled Reactor (TCR) or Thyristor Switched Reactor (TSR), Thyristor Switched Capacitor (TSC), Passive Filter

2.5.2 Static Synchronous Compensator (STATCOM)

According to definition of IEEE PES Task Force of FACTS Working Group:

A Static synchronous generator operates as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.

The STATCOM is the static counterpart of the rotating synchronous condenser but it generates/absorbs reactive power at a faster rate because no moving parts are involved. In principle, it performs the same voltage regulation functions as the SVC but in robust manner because unlike the SVC, its operation is not impaired by the presence of low voltage. The

STATCOM [2] has superior performance during low voltage condition as the reactive current can be maintained constant. (In a SVC, the capacitive reactive current drops linearly with the voltage at the limit of capacitive susceptance). It is even possible to increase the reactive current in a STATCOM under transient conditions if the devices are rated for the transient overload. The possibility of generating controllable reactive power directly, without the use of ac capacitors or reactors by various switching power converters was disclosed by Gyugi in 1976[3]. Functionality, from the stand point of reactive power generation, their operation is similar to that of an ideal synchronous machine whose reactive power output is varied by excitation control. Like the mechanically powered machine these converters can also exchange real power with the ac system if supplied from an appropriate, usually dc energy source. Because of these similarities with a rotating synchronous generator, they are termed Static Synchronous Generator (SSG). When SSG is operated without an energy source and with appropriate controls to function as shunt-connected reactive compensator, it is termed, analogously to the rotating synchronous compensator (condenser) a Static Synchronous Compensator (STATCOM) or Static Synchronous Condenser (STATCON).

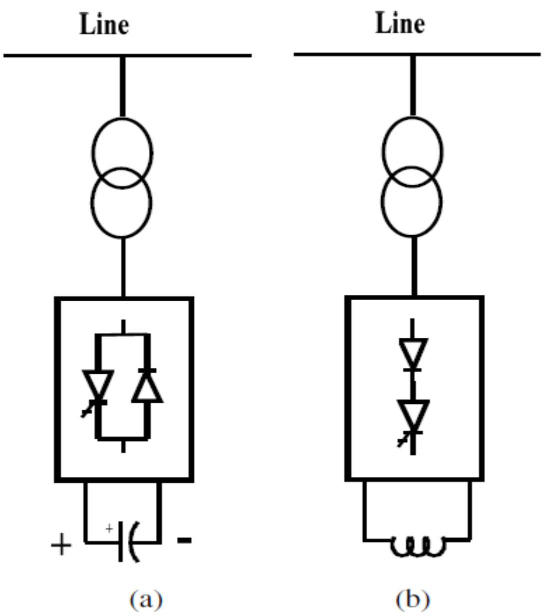


Fig. 2.3 Static Synchronous Compensator (STATCOM) based on (a) voltage sourced Converter (b) current-sourced converter.

2.6 Series Compensators:

Shunt compensation is ineffective in controlling the actual transmitted power which, at a defined transmission voltage, is ultimately determined by the series line impedance and the angle between the end voltages of line.

The ac power transmission line over long line has some series reactance and this will limited the power flow in the line. Series capacitive compensation is cancel a portion of the reactive line impedance and thereby increase the transmittable power. Due to the initiative of facts controllers variable series compensation is highly effective in both controlling power flow in the line and in improving stability. With the use of fast controls minimizing the effect of system disturbances, thereby reducing traditional stability margin requirements.

The effect of series compensation on the basic factors, determining accomplish maximal power transmission, steady-state power transmission limit, transient stability, voltage stability and power oscillation damping, will be examined. The series compensators are thyristor controlled series capacitor and static synchronous series compensator.

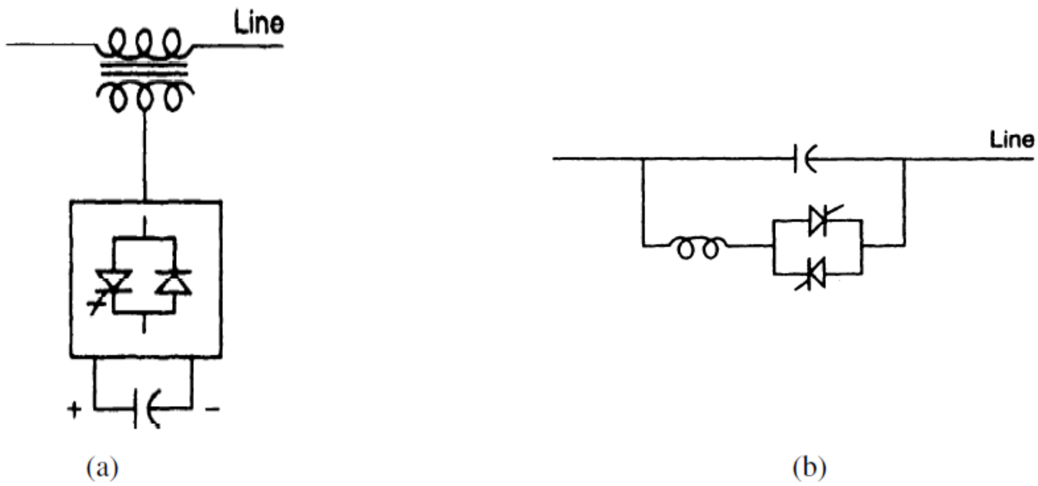


Fig. 2.4 (a) Static Synchronous Series Compensator (SSSC); (b) Thyristor-Controlled Series Capacitor (TCSC)

2.6.1 Static Synchronous Series Compensator (SSSC):

According to definition of IEEE PES Task Force of FACTS Working Group:

A static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. The SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behaviour of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real (resistive) voltage drop across the line.

SSSC is one the most important FACTS Controllers. It is like a STATCOM, except that the output ac voltage is in series with the line. It can be based on a voltage sourced converter in Figure 2.4(a). [3] Usually the injected voltage in series would be quite small compared to the line voltage, and the insulation to ground would be quite high. The transformer ratio is tailored to the most economical converter design. Without an extra energy source, SSSC can only inject a variable voltage, which is 90 degrees leading or lagging the current. The primary of the transformer and hence the secondary as well as the converter has to carry full line current including the fault current unless the converter is temporarily bypassed during severe line faults.

2.6.2 Thyristor Controlled Series Capacitor (TCSC):

According to definition of IEEE PES Task Force of FACTS Working Group:

A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance.

The TCSC connected is shown in figure 2.4(b), [3] is based on thyristor without the gate turnoff capability. It is an alternative to SSSC above and like an SSSC; it is a very important FACTS Controller.

FACTS Controllers are capable of controlling the network condition in a very fast manner and this unique feature of facts can be exploited to improve the stability of the power system. Among FACTS Controllers TCSC is the most important one and best known series FACTS Controller. It has been in use for many years to increase line power transfer as well as to enhance system stability. TCSC is a series FACTS device which allows rapid and continuous changes of the transmission line impedance. It has great application and potential in accurately regulating the power flow on a transmission line, damping inter-area power oscillations, mitigating the sub-synchronous resonance and improving the transient stability. The use of thyristor control to provide variable series compensation makes it attractive to employ series capacitors in long lines. A major advantage is that the SSR problem (Torsional Interaction) is significantly reduced. The feasibility of fast control of thyristor valves enables the improvement of stability and damping of oscillations using appropriate control strategies.

A variable reactor such as a Thyristor-Controlled Reactor (TCR) [2] is connected across a series capacitor. When the TCR firing angle is 180 degrees, the reactor becomes non conducting and the series capacitor has its normal impedance. As the firing angle is advanced from 180 degrees to less than 180 degrees, the capacitive impedance increases. At the other end, when the TCR firing angle is 90 degrees, the reactor becomes fully conducting, and the total impedance becomes inductive, because the reactor impedance is designed to be much lower than the series capacitor impedance. With 90 degrees firing angle, the TCSC helps in limiting fault current. The TCSC may be a single, large unit, or may consist of several equal or different-sized smaller capacitors in order to achieve a superior performance.

2.7 Unified Power Flow Control (UPFC):

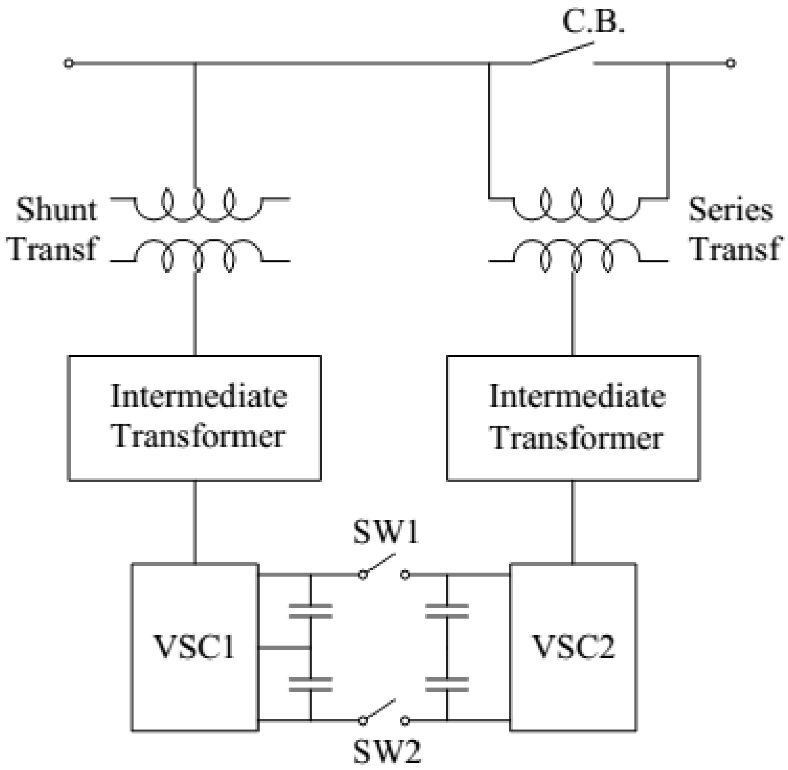


Fig. 2.5. Unified Power Flow Controller (UPFC)

The unified power flow controller (UPFC)[2] proposed by Gyugyi. It is the most versatile FACTS controller for the regulation of voltage and power flow in a transmission line.it consists of two voltage source converters (VSC) one shunt connected and other series connected. The DC capacitor is connected in between of the two converters which will provide dc voltage for converter operation. As UPFC consists of two converters that are coupled on DC side, the control of each converter is taken up individually .i.e we can control shunt converter separately and series converter separately. The maintenance of constant voltage is necessary and it is prerequisite of series and shunt converters. It is one of the most important and effective controller which will enhance transient stability, steady state stability and dynamic stability of the system.

Table 1: Comparison between FACTS Devices for Power System Stability Enhancement

S.No	Facts Device	Power System Stability Enhancement	Load Flow Control	Voltage Control	Transient Stability	Dynamic Stability
1	UPFC	YES	HIGH	HIGH	MEDIUM	MEDIUM
2	TCSC	YES	MEDIUM	LOW	HIGH	MEDIUM
3	SVC	YES	LOW	HIGH	LOW	MEDIUM
4	SSSC	YES	LOW	HIGH	MEDIUM	MEDIUM

From the above comparison table between FACTS Devices for Power System Stability Enhancement we say that for Dynamic Stability enhancement in power system all FACTS controllers will play same role all are having same capacity. For Load Flow control purpose in the power system UPFC is the most effective controller among all FACTS controllers. For Voltage Control purpose in the power system except TCSC all are having the same capacity and they will control effectively. For Transient Stability control in power system TCSC is the most effective one among all of FACTS[2] controllers, because of this only here we considered TCSC damping Controller for transient stability improvement and to damp out low frequency oscillations in the system.

2.8. Power System Stability

Transmission networks of modern power systems are becoming increasingly stressed because of growing demand and restrictions on building new lines. One of the consequences of such a stressed system is the threat of losing stability following a disturbance. FACTS devices are found to be every effective in stressing a transmission network for better utilization of its existing facilities without sacrificing the desired stability margin.

Power system stability is a complex subject that has challenged power system engineers for many years. Power system stability may be defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. The tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium is known as stability [4]. If the forces tending to hold machines in synchronism with one another are sufficient to overcome the disturbing forces, the system is said to remain stable. Conversely, instability means a condition denoting loss of synchronism or falling out of step. Stability considerations have been recognized as an essential part of power system planning for a long time. With interconnected systems continually growing in size and extending over vast geographical regions, it is becoming increasingly more difficult to maintain synchronism between various parts of a power system. For convenience of analysis, stability problems are classified into three basic types – steady state stability, dynamic stability and transient stability. Steady-state stability refers to the ability of the power system to regain synchronism after small and slow disturbances, such as gradual power changes. The dynamic stability is concerned with small disturbances lasting for a long time with the inclusion of automatic control devices. Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. Transient stability studies deals with the effects of large, sudden disturbances such as the occurrence of a fault, the sudden outage of a line or the sudden application or removal of loads. Stability depends on both the initial operating state of the system and the severity of the disturbance [1], [5].

2.8.1 Transient Stability _ Equal- Area Criterion:

The transient stability studies involve the determination of whether or not synchronism is maintained after the machine has been subjected to severe disturbances. This may be sudden application of load, loss of generation, loss of large load, or a fault on the system. In most disturbances, oscillations are of such magnitude that linearization is not permissible and the nonlinear swing equation must be solved. For a quick prediction of stability *equal-area criterion* method can be used [5]. This method is based on the graphical interpretation of the energy stored in the rotating mass as an aid to determine if the machine maintains its stability after a disturbance. The method is only applicable to a one - machine system connected to an infinite bus or a two machine system.

Consider a synchronous machine connected to an infinite bus. The swing equation with damping neglected is given by

$$\frac{H}{\pi f_o}\frac{d^2\delta}{dt^2} = (P_m - P_e) = P_a \tag{2.1}$$

where Pa is the accelerating power. From the above equation

$$\frac{d^2\delta}{dt^2} = \frac{\pi f_0}{H}(P_m - P_e) \tag{2.2}$$

Multiplying both sides of the equation by 2 $d\delta/dt$, we get

$$2\frac{d\delta}{dt}\frac{d^2\delta}{dt^2} = \frac{2\pi f_0}{H}(P_m - P_e)\frac{d\delta}{dt} \quad (2.3)$$

This may be written as

$$\frac{d}{dt}\left[\left(\frac{d\delta}{dt}\right)^2\right] = \frac{2\pi f_0}{H}(P_m - P_e)\frac{d\delta}{dt} \quad (2.4)$$

or

$$d\left[\left(\frac{d\delta}{dt}\right)^2\right] = \frac{2\pi f_0}{H}(P_m - P_e)d\delta \quad (2.5)$$

Integrating both sides

$$\left(\frac{d\delta}{dt}\right)^2 = \frac{2\pi f}{H}\int_{\delta_0}^{\delta}(P_m - P_e)d\delta \quad (2.6)$$

or

$$\frac{d\delta}{dt} = \sqrt{\frac{2\pi f_0}{H}\int_{\delta_0}^{\delta}(P_m - P_e)d\delta} \quad (2.7)$$

Equation (1.7) gives the relative speed of the machine with respect to the synchronously revolving reference frame. For stability, this speed must become zero at some time after the disturbance. Therefore, from (1.7), we have for the stability criterion

$$\int_{\delta_0}^{\delta}(P_m - P_e)d\delta = 0 \quad (2.8)$$

Consider the machine operating at the equilibrium point δ_0, corresponding to the mechanical power input $P_{mo} = P_{eo}$ as shown in Fig. 1.5. Consider a sudden step increase in input power represented by the horizontal line Pm1. Since Pm1 > Peo, the accelerating power on the rotor is positive and the power angle δ increases. The excess energy stored in the rotor during the initial acceleration is

$$\int_{\delta_0}^{\delta_1}(P_{m1} - P_e)d\delta = area \text{ abc =area } A_1 \quad (2.9)$$

With increase in δ, the electrical power increases, and when $\delta = \delta_0$ the electrical power matches the new input power Pm1. Even though the accelerating power is zero at this point, the rotor is running above synchronous speed; hence δ and electrical power Pe will continue to increase. Now Pm < Pe, causing the rotor to decelerate synchronous speed until $\delta = \delta_{\max}$. According to (1.8), the rotor must swing past point b until an equal amount of energy is given up by the rotating masses. The energy given up by the rotor as it decelerates back to synchronous speed is

$$\int_{\delta_0}^{\delta_1} (P_{m1} - P_e)d\delta = \text{area bde} = \text{area } A_2 \tag{2.10}$$

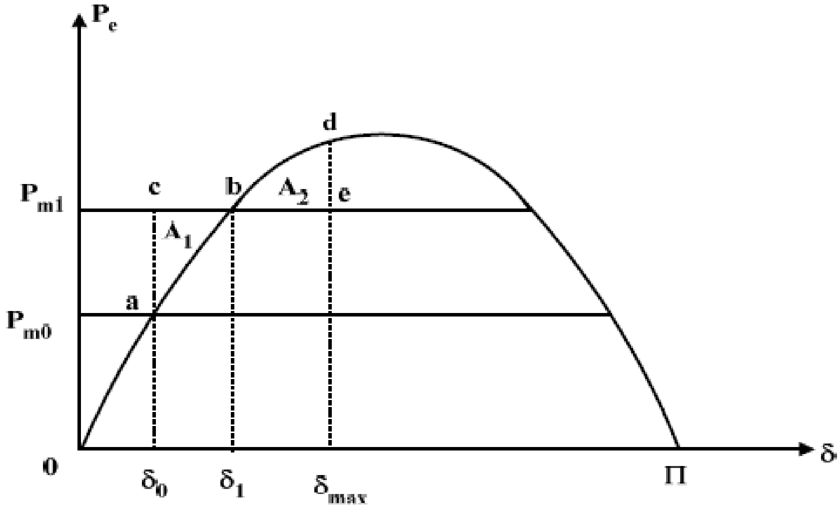


Fig. 2.6. Equal-area criterion – sudden change of load

The result is that the rotor swings to point b and the angle $\delta_{\max}$, at which point

$$|\text{ area } A_1 \ | \ = | \text{ area } A_2 \ | \tag{2.11}$$

This is known as the *equal-area criterion*. The rotor angle would then oscillate back and forth between δ_0 and $\delta_{\max}$ at its natural frequency. The damping present in the machine will cause oscillations to subside and the new steady state operation would be established at point *b*.

2.8.2 Factors Influencing Transient Stability:

Many factors affect the transient stability of a generator in a practical power system [4]. From the small system analyzed above, the following factors can be identified:

- The post-disturbance system reactance as seen from the generator. The weaker the post-disturbance system, the lower the Pmax will be.
- The duration of the fault-clearing time. The longer the fault is applied, the longer the rotor will be accelerated and the more kinetic energy will be gained. The more energy that is gained during acceleration, the more difficult it is to dissipate it during deceleration.
- The inertia of the generator. The higher the inertia, the slower the rate of change of angle and the lesser the kinetic energy gained during the fault.

- The generator internal voltage (determined by excitation system) and infinite bus voltage (system voltage). The lower these voltages, the lower the Pmax will be.
- The generator loading before the disturbance. The higher the loading, the closer the unit will be to Pmax, which means that during acceleration, it is more likely to become unstable.
- The generator internal reactance. The lower the reactance, the higher the peak power and the lower the initial rotor angle.
- The generator output during the fault. This is a function of faults location and type of Fault.

CHAPTER 3

Modelling of Single Machine Infinite Bus System with Exciter and TCSC Controllers

3.1 Single Machine Infinite Bus System:

In this, we focus our attention on single machine infinite bus (SMIB) power systems. Since a SMIB system qualitatively exhibits important aspects of the behaviour of a multi-machine system and is relatively simple to study, it is extremely useful in describing the general concepts of power systems stability, the influence of various factors upon stability, and alternative controller concepts. An infinite bus is a source of constant frequency and voltage either in magnitude and angle

We consider the particular SMIB power system arrangement shown in Fig.3.1. The actual dynamic response of a synchronous generator in a practical power system when a fault occurs is very complicated including much nonlinearity such as the magnetic saturation. However, the classical third order dynamic generator model has been commonly used for designing the excitation controller.

3.2 Modelling of SMIB system:

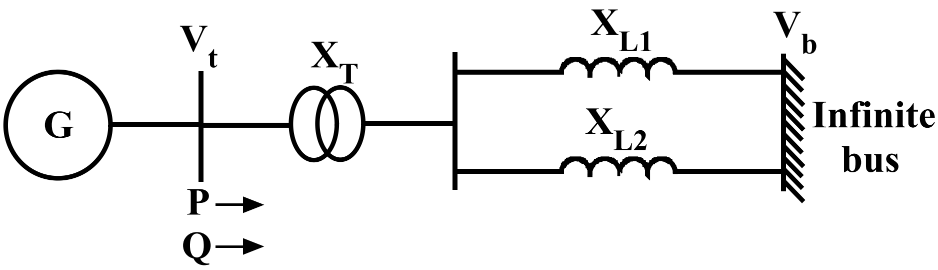


Fig.3.1 A single machine infinite bus power system.

The classical third-order dynamical model of a SMIB power system Fig.3.1 can be written as follows [1]:

$$\frac{d\delta(t)}{dt} = \omega(t) - \omega_0 \tag{3.1}$$

$$\frac{d\omega(t)}{dt} = -\frac{D}{2H}\left[\omega(t) - \omega_0\right] - \frac{\omega_0}{2H}\left[P_m - P_e(t)\right] \tag{3.2}$$

$$\frac{dE_q^1(t)}{dt} = \frac{1}{2H}\left[E_F(t) - (X_d - X_d^1)\, I_d(t) - E_q^1(t)\right] \tag{3.3}$$

Where

$$E_{fd}(t) = K_A E_F(t) \tag{3.4}$$

$$E_q(t) = \frac{X_{ds}}{X_{ds}^1} E_q^1(t) - \frac{X_d - X_d^1}{X_{ds}^1} V_b \cos(\delta(t)) \tag{3.5}$$

$$P_e(t) = \frac{E_q(t)V_b}{X_{ds}} \sin(\delta(t)) \tag{3.6}$$

$$X_{ds} = X_d + X_T + X_L \tag{3.7}$$

$$X_{ds}^1 = X_d^1 + X_T + X_L \tag{3.8}$$

$\delta(t)$ is the rotor angle of the generator (radians), $\omega(t)$ is the speed of the rotor of the generator (radian/sec), ω_o is the synchronous machine speed (radian/sec), D is the damping constant (pu), H is the inertia constant , P_m is the mechanical input power of the generator (pu), $P_e(t)$ is the active electrical power delivered by the generator (pu), $E_q(t)$ isthe EMF of the q-axis of the generator (pu), $E^1_q(t)$ the transient EMF in the q-axis of the generator (pu), $E_{fd}(t)$ is the equivalent EMF in the excitation winding of the generator (pu), T'_{do} is the d-axis transient short circuit time constant (sec), K_A is the gain of the excitation amplifier, $E_{fd}(t)$ is the control input of the excitation amplifier with gain K_A, X_{ds} is the total direct reactance of the system (pu), X'_{ds} is the total transient reactance of the system (pu), X_d is the d-axis reactance of the generator (pu), X'_d is the d-axis transient reactance of the generator (pu),
X_T is the reactance of the transformer (pu), X_L is the reactance.

3.3 Power system stabilizer:

The basic function of Power system stabilizer (PSS) is to add damping to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signal(s).and it can improve power system dynamic performance. Commonly used input signals to the power system stabilizer are shaft speed, terminal frequency and power. Power system dynamic performance is improved by the damping of system oscillations. To provide damping, the stabilizer must produce a component of electrical torque in phase with the rotor speed deviations. The purpose of a PSS is to introduce a damping torque component, a logical signal to use for controlling generator excitation is the speed deviation.PSS is a very effective method of enhancing small-signal stability performance.

3.4 Modelling of Power system stabilizer:

Models for different types of excitation systems in use are described in [1]. We will illustrate the method of incorporating these models into a transient stability program by considering the excitation system model shown in Fig.3.2. It represents a bus-fed thyristor excitation system (classified as type STIA1) with an automatic voltage regulator (AVR) and a power system stabilizer (PSS).

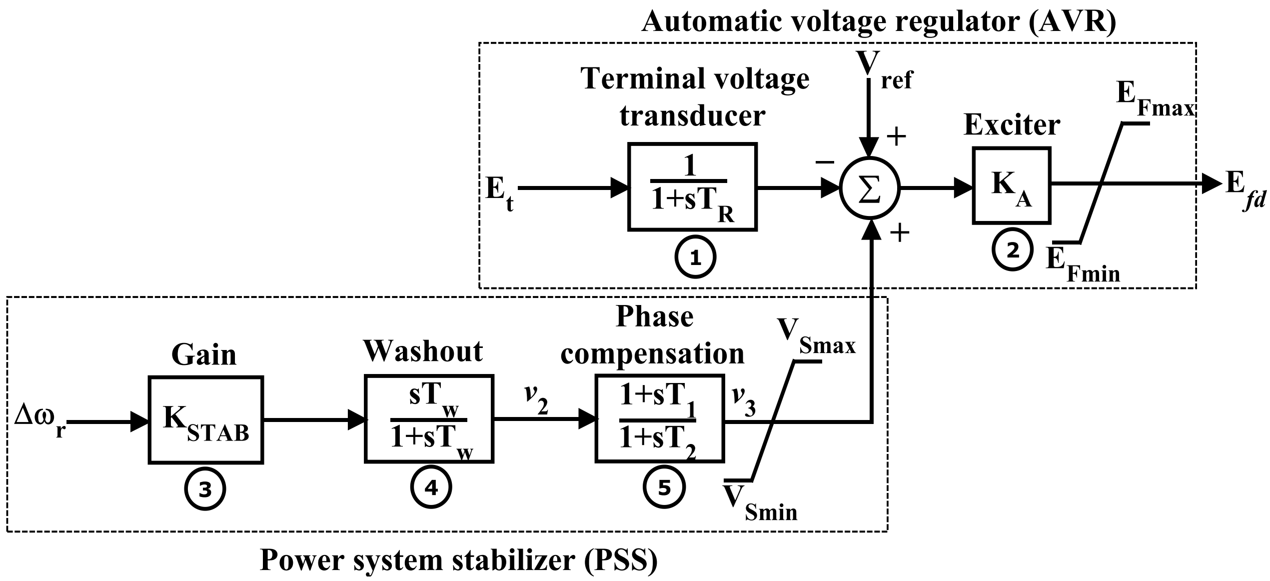


Fig.3. 2 Thyristor excitation system with AVR and PSS

The AVR regulator model (block 1) shown in Fig.2 has been simplified to include only those elements that are considered necessary for representing a specific system. Parameter T_R represents the terminal voltage transducer time constant. A high exciter gain (block 2), without transient gain reduction or derivate feedback, is used. The nonlinearity associated with the model is that due to the ceiling on the exciter output voltage represented by (E_{Fmax}, E_{Fmin}) and PSS output voltage (V_{Smax}, V_{Smin}).The PSS representation in Fig.2 consists of three blocks: a phase compensation block, a signal washout block, and again block. The phase compensation block (block 5) provides the appropriate phase-lead characteristic to compensate for the phase lag between the exciter input and the generator electrical (air-gap) torque. The signal washout block (block 4) serves as a high-pass filter, with the time constant T_W high enough to allow signals association with oscillations in w to pass unchanged. Without it, steady changes in speed would modify the terminal voltage. The stabilizer gain K_{STAB}(block3) determines the amount of damping introduced by the PSS.

From block 1 of Fig.2, we may write:

$$pv_1 = \frac{1}{T_R}(E_t - v_1) \tag{3.9}$$

From blocks 3 and 4,

$$pv_2 = K_{STAB} p\Delta\omega_r - \frac{1}{T_W} v_2 \tag{3.10}$$

With $p\Delta\omega_r$ given by Equation (2). From block 5,

$$pv_3 = \frac{1}{T_2}(T_1 pv_2 + v_2 - v_3) \tag{3.11}$$

With pv_2 given by Equation (10). The stabilizer output V_S is

$$V_S = v_3 \tag{3.12}$$

With

$$V_{S\max} \geq V_S \geq V_{S\min} \tag{3.13}$$

From block 2, the exciter output voltage is

$$E_{fd} = K_A[V_{ref} - v_1 + v_s] \tag{3.14}$$

With

$$E_{F\max} \geq E_{fd} \geq E_{F\min} \tag{3.15}$$

Initial value of excitation system variables

$$v_1=E_t,\ v_2= 0,\ V_S=0 \tag{3.16}$$

The AVR reference is

$$V_{ref} = \frac{E_{fd}}{K_A} + v_1 \tag{3.17}$$

Thus V_{ref} takes a value appropriate to the generator loading condition prior to the disturbance.

3.5 Thyristor Controlled Series Capacitor (TCSC):

FACTS Controllers are capable of controlling the network condition in a very fast manner and this unique feature of facts can be exploited to improve the stability of the power system. Among FACTS Controllers TCSC is the most important one and best known series FACTS Controller. It has been in use for many years to increase line power transfer as well as to enhance system stability. TCSC [2] is a series FACTS device which allows rapid and continuous changes of the transmission line impedance. It has great application and potential in accurately regulating the power flow on a transmission line, damping inter-area power oscillations, mitigating the sub-synchronous resonance and improving the transient stability.

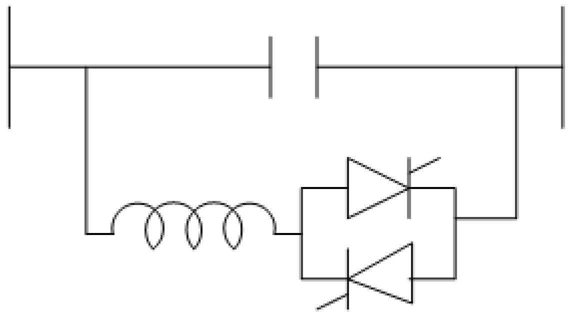


Fig.3.3 Strucutre of TCSC controller

3.5.1 Operation of TCSC:

A single line diagram of a TCSC is shown in Fig.3.4 which shows two modules connected in series. There can be one or more modules depending on the requirement[2]. To reduce the costs, TCSC may be used in conjunction with fixed series capacitors.

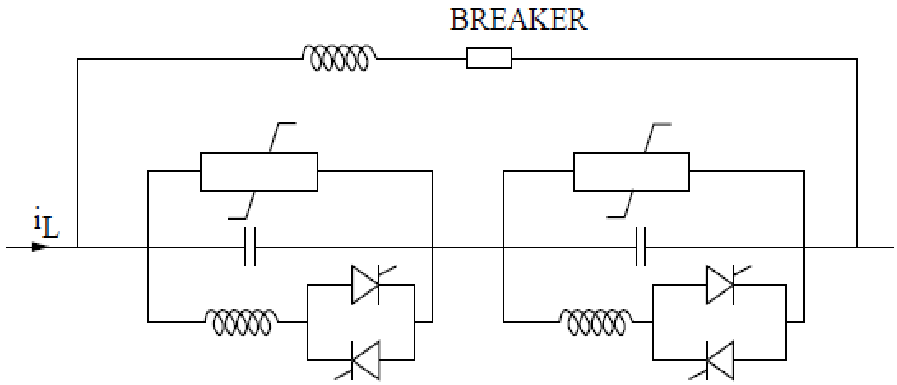


Fig. 3.4 Single Line Diagram of a TCSC

(a) **By Passed**

Here the thyristor valves are gated for 180^0conduction (in each direction) and the current flow in the reactor is continuous and sinusoidal. The net reactance of the module is slightly inductive as the susceptance of the reactor is larger than that of the capacitor. During this mode, most of the line current is flowing through the reactor and thyristor valves with some current flowing through the capacitor. This mode is used mainly for protecting the capacitor against over voltages (during transient over currents in the line).This mode is also termed as TSR (Thyristor Switched Reactor) mode.

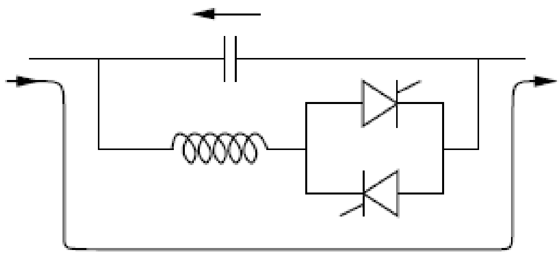


Fig.3.4 (a) By passed

(b)Inserted with Thyristor Valve Blocked

In this operating mode no current flows through the valves with the blocking of gate pulses. Here, the TCSC reactance is same as that of the fixed capacitor and there is no difference in the performance of TCSC in this mode with that of a fixed capacitor. Hence this operating mode is generally avoided. This mode is also termed as waiting mode.

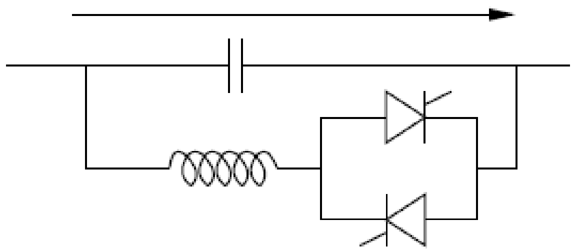


Fig.3.4 (b) Thyristor blocked

(c) Inserted with Vernier Control

In this operating mode, the thyristor valves are gated in the region of ($\alpha_{min} < \alpha < 90^0$) such that they conduct for the part of a cycle. The effective value of TCSC reactance (in the capacitive region) increases as the conduction angle increases from zero. α_{min} is above the value of α corresponding to the parallel resonance of TCR and the capacitor (at fundamental frequency). In the inductive vernier mode, the TCSC (inductive) reactance increases as the conduction angle reduced from 180^0.Generally, vernier control is used only in the capacitive region and not in the inductive region.[2]

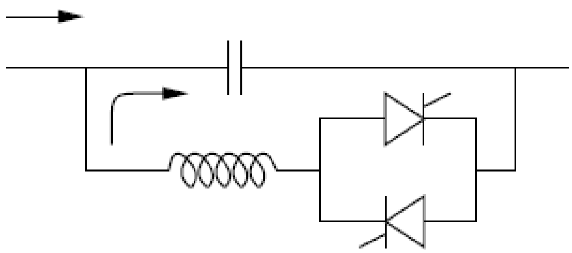


Fig.3.4 (c) Vernier Operation

3.6 Modelling of Thyristor Controlled Series Capacitor (TCSC):

A TCSC Controller consists of a fixed series capacitor (FC) in parallel with a thyristor controlled reactor (TCR). The TCR is formed by a reactor in series with a bi-directional thyristor valve that is fired with a phase angle α ranging between 90^0 and 180^0 with respect to the capacitor voltage [6]. For the load flow and dynamic stability analysis studies, a TCSC can be modelled as a variable reactance. In this modelling approach, the effect of the FACTS devices on the power flow is represented as a variable current injection at the terminal buses of the lines.The use of thyristor control to provide variable series compensation makes it attractive to employ series capacitors in long lines. A major advantage is that the SSR problem (Torosional Interaction) is significantly reduced. The feasibility of fast control of thyristor valves enables the improvement of stability and damping of oscillations using appropriate control strategies.

According to the variation of the conduction angle (σ) or the thyristor firing angle (α), the process can be modelled as a fast switch between corresponding reactance offered to the power system. There is a steady state relationship between α and the reactance X_{TCSC}. This relationship can be described by the following equation :

$$X_{T\csc} = X_c - \frac{X_c^2\left(\sigma+\sin\sigma\right)}{\left(X_c - X_p\right)\pi} + \frac{4X_c^2\cos^2\left(\sigma/2\right)\left[k\tan\left(k\sigma/2\right)-\tan\left(k\sigma/2\right)\right]}{\left(X_c - X_p\right)\left(k^2-1\right)\pi} \quad (3.18)$$

Where

X_c :Nominal reactance of the fixed capacitor C

X_p :Inductive reactance of inductor L connected in parallel with C

σ : Conduction angle of TCSC, $\sigma = 2\left(\pi-\alpha\right)$

α : Firing angle of TCSC

k : Compensation ratio, $k = \sqrt{\frac{X_c}{X_p}}$

A TCSC is modelled here as a variable capacitive reactance within the operating region defined by the limits imposed by α.

Thus,

$$X_{TCSC_{\min}} \le X_{TCSC} \le X_{TCSC_{\max}},$$
$$X_{TCSC_{\min}} = X_{TCSC}\left(\alpha_{\max}\right) = X_c$$
$$X_{TCSC_{\max}} = X_{TCSC}\left(\alpha_{\min}\right)$$

3.6.1 Damping controller for the TCSC:

The Damping controller is designed to produce an electric torque in phase with the speed deviation according to the phase compensation method. Here two types of damping controllers have been proposed for the TCSC.

(a) Structure of PI based TCSC controller:

The structure of proportional-integral (PI) controller based TCSC is shown in Fig.3.5. TCSC controller input signal is speed deviation (Δω) and the output signal is the stabilizing signal. (i.e. deviation in conduction angle Δσ). It comprises of gain block, signal washout block and proportional-integral controller block. An optimum controller can be obtained by suitable selection of Tw, KT, KP and KI with some designing technique.

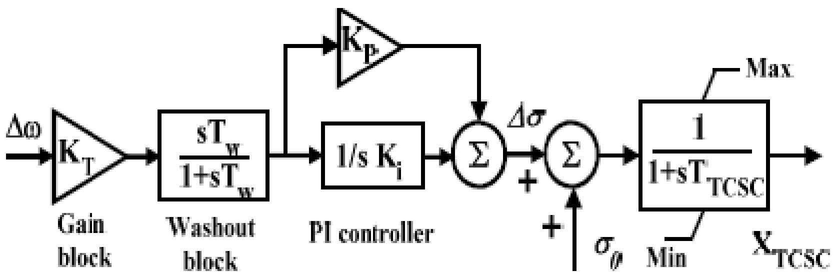


Fig.3.5 Structure of PI based TCSC Controller

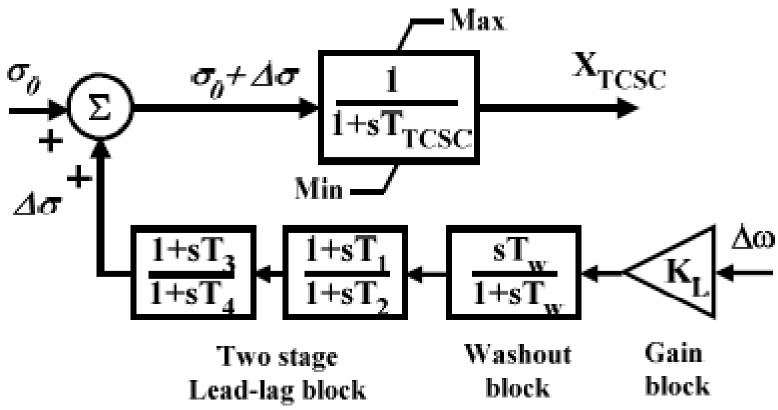


Fig.3.6 Structure of Lead-Lag based TCSC Controller.

(b) Structure of Lead-Lag based TCSC Controller:

The commonly used lead–lag structure is chosen in this study as a TCSC Controller. The structure of the LL TCSC Controller is shown in Fig.3.6 [7]. The signal wash out block is a high pass filter that prevents the steady changes in the speed by modifying the conduction angle. The value of washout time constant Tw should be high enough to allow signals associated with rotor oscillation to pass unchanged. Tw may be in the range of 1-20 sec. The phase lead compensator is used for the phase lag between the angular speed and the resulting electrical torque, so that the TCSC controller produces a component of electrical torque in phase with the rotor speed deviation. The gain of TCSC controller is chosen such that it provides satisfactory damping. Here $\sigma = \sigma 0+\Delta\sigma$, $\sigma 0$ = initial value of conduction angle. Change in conduction angle $\Delta\sigma$ changes the initial compensation. The structure of Lead Lag based TCSC controller is shown in Fig.3.6. Out of PI-based TCSC controller and Lead-Lag based TCSC controller conventional lead-lag based TCSC controller is most widely adopted in industrial applications because of simple structure, easy to design and low cost.

CHAPTER 4

Co-ordinated design of PSS and TCSC damping Controllers in Single Machine Infinite Bus system using PSO

4.1 Particle Swarm Optimization (PSO):

The conventional technique can be used to design a robust controller but the designed controller by this method is usually complicated with high order and the control parameters values are difficult to select. To solve this problem we propose a new design technique called "Particle swarm optimization". Particle Swarm Optimization (PSO) technique, developed by Kennedy and Eberhart [8], is found applicability and has been used extensively in solving various problems in power systems. Introduction of PSO to search for optimal settings of rule based PSS have been discussed in [9]. Multi-objective design of multi-machine power system stabilizers using particle swarm optimization (PSO) is proposed in [10]. Power system stability enhancement via excitation and FACTS-based stabilizers is thoroughly investigated in [11]. Here, eigenvalue-based objective function to increase the system damping and improve the system response is developed and it is optimized using real-coded genetic algorithm. However, from an evolutionary point of view, the performance of the PSO is better than that of GA [12] and the authors claimed that PSO arrives at its final parameter values in fewer generations than the GA. Moreover the authors tested several stabilizers like PSS, SVC, TCSC and TCPS individually to enhance system stability.

Fig.4.1.Flock of birds collectively foraging for food

In literature several researchers proposes the coordination of PSS with FACTS controllers to enhance dynamic performance of the power system. In [13], the authors discussed global tuning procedure for PSS and FACTS devices using a parameter-constrained nonlinear optimization algorithm. A robust coordinated design of a PSS and TCSC based stabilizer is thoroughly investigated in [14], here an eigenvalue-based objective function is optimized using GA. In [15] the authors develop a novel algorithm for simultaneous coordinated designing of PSS and TCSC based controllers using bacterial swarm optimization.

The Advantages of PSO over other traditional optimization techniques:

i. PSO is a population-based search algorithm i.e., PSO has implicit parallelism. This property ensures PSO to be less susceptible to getting trapped on local minima.

ii. PSO uses objective function information to guide the search in the problem space. Therefore, non-differentiable objective functions can be easily dealed by PSO.

iii. PSO uses probabilistic transition rules, not deterministic rules. More complicated and uncertain area can be easily search by PSO algorithm. From this we can conclude that when compared to conventional methods PSO is more flexible and robust.

iv. When compared with GA and other heuristic algorithms, PSO has more flexibility to control the balance between the global and local exploration of the search space.

PSO has a flexible and well balanced mechanism to enhance the global and local exploration abilities. Compare to GA, PSO is easy to implement and it consists of only few parameters to adjust. The position and velocity vectors of the ith particle in the D-dimensional space can be represented as $X_i = (x_{i1}, x_{i2}, \ldots\ldots\ldots, x_{id})$ and $V_i = (v_{i1}, v_{i2}, \ldots\ldots\ldots, v_{id})$ respectively. The particles in the optimization problem share their information with each other and run towards the best trajectory to find optimum solution in iterative process.

In each iteration particles will update their velocities and positions by using the following equations:

$$V_{i,\, iter+1} = wV_{i,\, iter} + c_1 r_1 (P_{i,\, iter}^{best} - X_{i,\, iter}) + c_2 r_2 (G_{i,\, iter}^{best} - X_{i,\, iter}) \tag{4.1}$$

$$X_{i,\, iter+1} = X_{i,\, iter} + V_{i,\, iter+1} \tag{4.2}$$

Where $V_{i,\, iter}$ and $X_{i,\, iter}$ represent the velocity vector and the position vector of ith particle at iteration ‘iter’, $P_{i,\, iter}^{best}$ and $G_{i,\, iter}^{best}$ are personal best position of ith particle and global best position of swarm in the iteration ‘iter’. The constants c_1 and c_2 are the positive cognitive and social components that are responsible for varying the particle velocity towards the pbest and gbest, respectively, r_1 and r_2 are two random numbers in the range [0-1]. The inertia weight w is responsible for dynamically adjusting the velocity of the particles. To enhance the efficiency of PSO, one can adjust the inertia weight w to linearly reduce during the iterations. The inertia weight is updated by the following equation

$$w = (w_{\max} - w_{\min}) \times \left(\frac{iter_{\max} - iter}{iter_{\max}} \right) + w_{\min} \tag{4.3}$$

where $iter_{\max}$ is the maximum number of iterations and iter is the current number of iteration. $w_{\max}$ and $w_{\min}$ are maximum and minimum values of inertia weight respectively. The typical range of w from 0.9 at the beginning of the search to 0.4 at the end of the search [16].

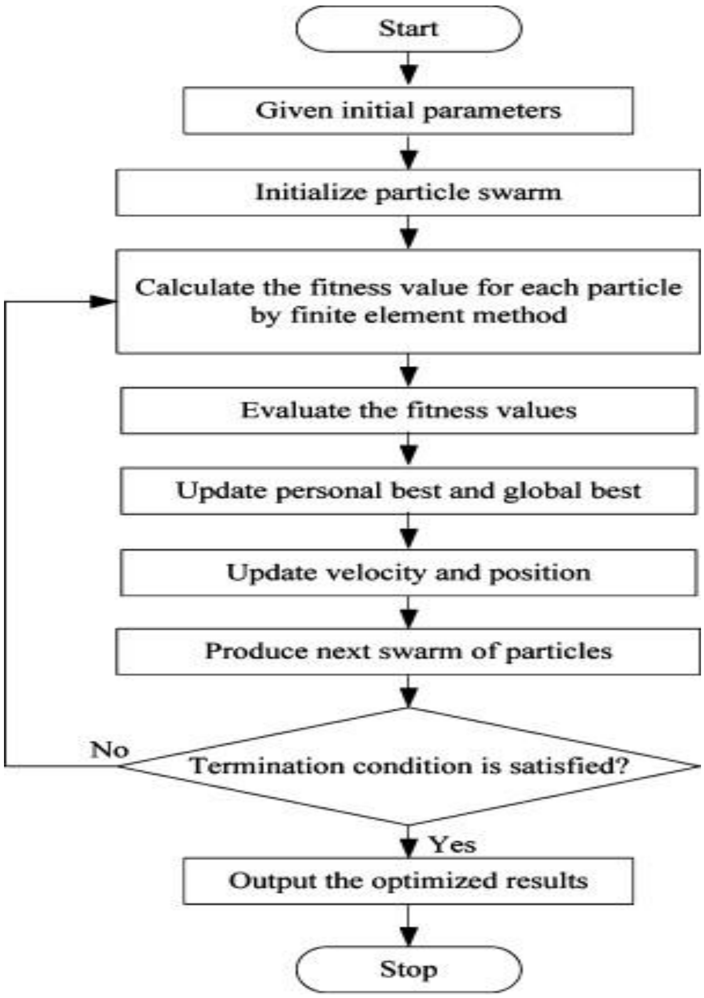


Fig.4.2.Flowchart of the proposed PSO technique

The conventional PSO has a drawback of its inadequate convergence towards global optima. The proposed technique can be made more effective by adding some new parameters to existing one and made constants c_1 and c_2 as a function of iterations which will update automatically after every loop and it will provide adequate convergence. Here we will study the same optimization technique with some changes made in it. To guarantee the algorithm convergence and avoiding the explosion of the particle swarm (i.e. the state where the particles velocities and positional coordinates careen toward infinity) an advance PSO technique was introduced by Clerc et al. [17]. The advanced PSO hosting a new parameter called constriction factor 'K' in the velocity equation. Hence, the particles in the swarm can update their velocities and positions by using the following equations:

$$V_{i,\,iter+1} = K\,[wV_{i,\,iter} + c_1 r_1 (P_{i,\,iter}^{best} - X_{i,\,iter}) + c_2 r_2 (G_{i,\,iter}^{best} - X_{i,\,iter})] \tag{4.4}$$

$$X_{i,\,iter+1} = X_{i,\,iter} + V_{i,\,iter+1} \tag{4.5}$$

where $K = \dfrac{2}{\left| 2 - \varphi - \sqrt{\varphi^2 - 4\varphi} \right|}$, $\varphi = c_1 + c_2, \varphi > 4$

Usually c_1 and c_2 are selected in the range of 0 to 4.

In population based optimization methods, the policy is to encourage the individuals to roam through the entire search space without clustering around local optima during the initial stages. However, during latter stages to find the optimum solution efficiently convergence towards the global optima should be encouraged. The concept of time-varying acceleration coefficients (TVAC) c_1 and c_2 in addition to time-varying inertia weight factor is introduced in advanced adaptive PSO technique such that AAPSO can efficiently control the local search and provide adequate convergence towards the global optimum solution. During initial stages a large c_1 and small c_2 allows the particles to move around search space instead of moving the population best prematurely. At latter stages a small c_1 and large c_2 allows the particles to converge towards the global optima. Acceleration coefficients are adaptively changed as follows [18]

$$c_1 = c_1^f \left(\frac{iter}{iter_{\max}}\right) + c_1^i \left(\frac{iter_{\max} - iter}{iter_{\max}}\right), c_1^f < c_1^i \tag{4.6}$$

$$c_2 = c_2^f \left(\frac{iter}{iter_{\max}}\right) + c_2^i \left(\frac{iter_{\max} - iter}{iter_{\max}}\right), c_2^f > c_2^i \tag{4.7}$$

Where c_1^i, c_2^i and c_1^f, c_2^f are initial and final values of the acceleration coefficients.

4.2 SMIB with PSS and TCSC :

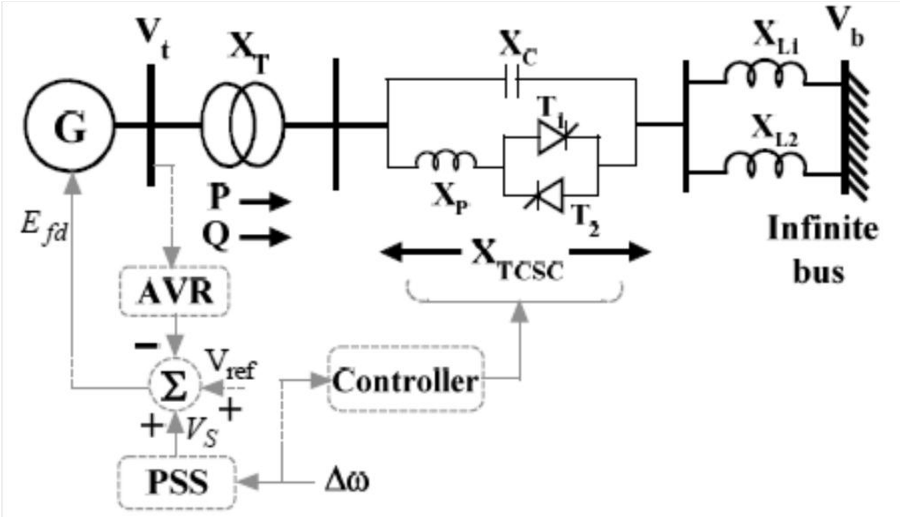


Fig. 4.3.Single-machine infinite-bus power system with PSS and TCSC controller.

4.2.1 Simultaneous Coordinated Design using Particle Swarm Optimization

The proposed controller must be able to work well under all operating conditions, while the improvement for the damping of the critical modes is necessary. Since the selection of the TCSC damping controller and PSS parameters is a complex optimization problem. Thus, to acquire an optimal combination and to improve the optimization synthesis and find the global optimum value an PSO algorithm has been employed [19]. A performance index based on the system dynamics after an impulse disturbance alternately occurs in the system is organized and used as the objective function for the design problem. In this study, an ITAE is taken as the objective function. Since the operating conditions in the power systems are often varied, a performance index for an operating point (Nominal loading) is defined as follows:

Objective function: $$\text{ITAE} = \int_0^{t_{sim}} t|\omega_1(t)-\omega_0(t)|dt \tag{4.8}$$

Where $\omega_1(t), \omega_0(t)$ are measured speeds and reference speeds and t_{sim} is the time range of simulation In order to improve the system response in terms of the settling time and overshoots we have to minimize this objective function. The design problem can be formulated as the following constrained optimization problem, where the constraints are the POD (power oscillation damping) controller parameter bounds.

For minimization of objective function constrain limits are

$$K_{ST}^{\min} \le K_{ST} \le K_{ST}^{\max} \tag{4.9}$$

$$T_1^{\min} \le T_1 \le T_1^{\max} \quad (4.10)$$

$$T_2^{\min} \le T_2 \le T_2^{\max} \quad (4.11)$$

. Where, KA and TA represent the gain and time constant respectively. KST is gain of the stabilizer block, TW is wash out time and T1, T2, T3, T4 are the time constants of lead-lag blocks in the damping controllers. The proposed approach employs the PSO to solve this optimization problem and search for an optimal set of power damping controller parameters. It is emphasized that with this procedure, robust stabilizer, enable to operate satisfactorily over a wide range of the operating conditions, are obtained. The flowchart of the optimization based coordinated design is shown below [19].

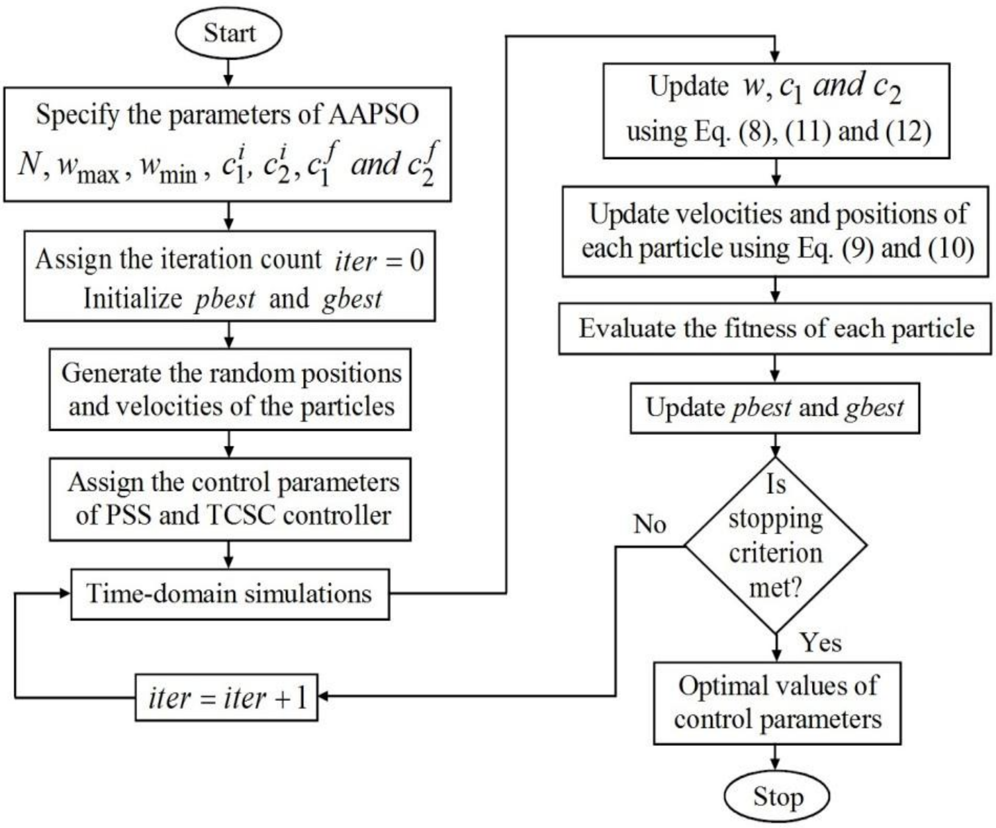


Fig. 4.4. Flowchart of optimization based coordinated designing

The optimization of the TCSC controller parameters is carried out by evaluating the objective cost function. In order to acquire better performance, number of iterations, number of particles, particle size, c, c1 and c2 are chosen as 200, 40, 10, 2, 2 and 1, respectively. It should be noted that the PSO algorithm is run several times and then optimal set of coordinated controller parameters is selected.

CHAPTER 5

Co-ordinated design of PSS and TCSC damping Controllers in Multi-machine power system using PSO

5.1 Classical model of Multi machine system:

The classical model of synchronous machine is used to study the stability of a power system for a period of time during which the system dynamic response is dependent largely on the stored kinetic energy in the rotating masses. The classical model is the simplest model is used in studies of a power system dynamics and requires minimum amount of data [20].

The following assumptions are used for a system of multi machine power system

i. Mechanical power input is constants.
ii. Loads are represented by passive impedances.
iii. Damping is negligible.
iv. The mechanical rotor angle of a machine coincides with the voltage behind the transient reactance.

This model is useful for stability analysis. A nonlinear dynamic model can describe a multi machine power system in figure 5.1 (3M-9 BUS) with three generators and three loads, in which the first machine is chosen as the reference machine.

The general current equation of the power system is

$$I=V[Y] \tag{5.1}$$

The matrix form is

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \tag{5.2}$$

Where I is current flow in the system, V represents the voltage and Y represents the admittance of the system.

5.2 Power Flow Solution by Newton-Rapshon Method:

Here, Load flow analysis is carried out for three machine nine bus system using Newton-Raphson approach. From this analysis we will know the amount of power flowing from one bus to another bus and we will know line losses and total losses occurred in the lines and in the system.

5.2.1 Newton-Raphson Approach

The Newton-Raphson (NR) method is a powerful method of solving non-linear algebraic equations. Because of its quadratic convergence, Newton's method is mathematically superior to the Gauss-Seidel method and is less prone to divergence with ill-conditioned problems. It works faster, and is sure to converge in most cases as compared to the Gauss-Siedel (GS) method. It is indeed the practical method of load flow solution of large power networks. Its only drawback is the large requirement of computer memory, which can be overcome through a compact storage scheme. One of the main strengths of the Newton-Raphson method is its reliability towards convergence. Contrary to non Newton-Raphson solutions, convergence is independent of the size of the network being solved and the number and kinds of control equipment present in the system. Hence in the proposed work Newton-Raphson method is preferred [21]-[22].

Advantages of NR method:

- It exhibits quadratic convergence. Usually it takes 3 iterations. Number of iterations is independent of system size
- It can work on overloaded and ill-conditioned system.
- Better convergence due to updation of voltages and phase angle of all buses simultaneously.

Disadvantages of NR method:

- High memory requirement, however, with the use of sparsity technique the memory requirement is drastically reduced.
- It needs good initial guess voltages, two iteration of Guess-Seidel method are run initially to get good initial guess voltages NR method.
- Bad initial guess voltages may lead to numerical divergence.

5.3 Three-machine nine-bus system:

A classical study will be presented here on nine bus power systems that have three generators and three loads as shown in fig.5.1. The classical model of synchronous machine is used to study the stability of a power system for a period of time during which the system dynamic response is dependent largely on the stored kinetic energy in the rotating masses. The classical model is the simplest model is used in studies of a power system dynamics and requires minimum amount of data. A classical study will be presented here on nine bus power systems that have three generators and three loads as shown in above. The input bus data for the considered system are given in Table 5.1 and input transmission line data given in Table 5.2 [20]. The transmission line impedances and line charging admittances are in per unit.

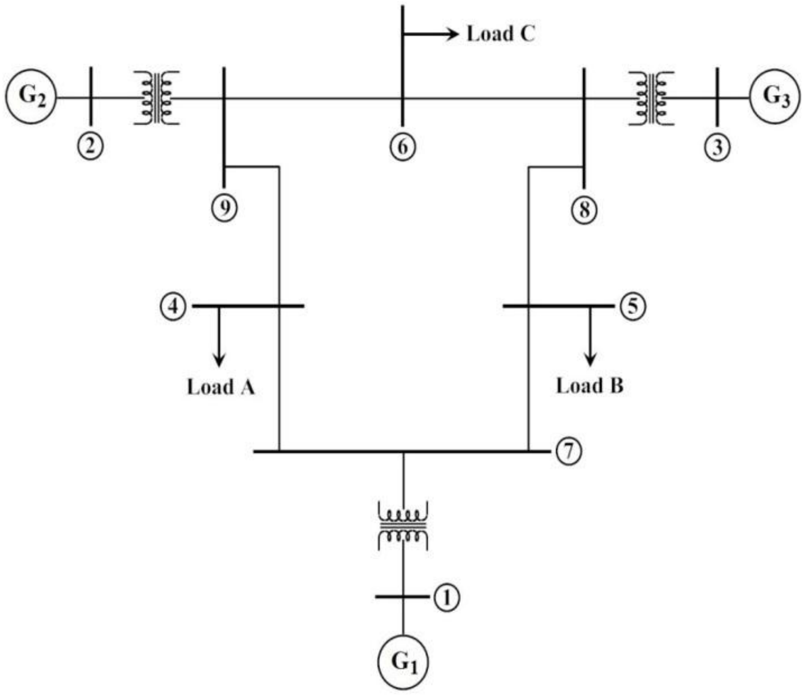


Fig.5.1. Single line diagram of Three-machine nine-bus system

Table 5.1: Input Bus Data for Three Machine Nine Bus System

Bus no	Type	Voltage		Generation		load	
		|v|	θ	P	Q	P	Q
1	slack	1.040	0.000	0.000	0.000	0.000	0.000
2	P-V	1.025	0.000	1.63	0.000	0.000	0.000
3	P-V	1.025	0.000	0.85	0.000	0.000	0.000
4	P-Q	0.000	0.000	0.000	0.000	1.25	0.5
5	P-Q	0.000	0.000	0.000	0.000	0.90	0.30
6	P-Q	0.000	0.000	0.000	0.000	1.00	0.35
7	P-Q	0.000	0.000	0.000	0.000	0.000	0.000
8	P-Q	0.000	0.0 00	0.000	0.000	0.000	0.000
9	P-Q	0.000	0.000	0.000	0.000	0.000	0.000

Assuming base quantity of 100MVA and 100KV

Table 5.2. Input Transmission Line Data (p.u.)

Bus no	Line Code	Impedance (R+jX)	Line charging admittance
1	1-7	0+j0.0576	0.000
2	7-4	0.01+j0.085	0+j0.088
3	7-5	0.017+j0.092	0+j0.079
4	4-9	0.032+j0.061	0+j0.153
5	5-8	0.039+j0.17	0+j0.179
6	2-9	0+j0.0625	0.000
7	9-6	0.0085+j0.07	0+j0.0745
8	6-8	0.0119+j0.10	0+j0.1045
9	3-8	0+j0.0586	0.000

Table 5.3 Bus data after TCSC included in the system

Bus no	Type	Voltage		Generation		Load	
		|v|	θ	P	Q	P	Q
1	slack	1.040	0.000	0.732	0.243	0.000	0.000
2	P-V	1.025	5.574	1.63	0.021	0.000	0.000
3	P-V	1.025	2.405	0.85	-0.12	0.000	0.000
4	P-Q	0.998	-3.397	0.000	0.000	1.25	0.5
5	P-Q	1.015	-4.510	0.000	0.000	0.90	0.30
6	P-Q	1.018	-2.364	0.000	0.000	1.00	0.35
7	P-Q	1.027	-2.264	0.000	0.000	0.000	0.000
8	P-Q	1.033	-0.291	0.000	0.000	0.000	0.000
9	P-Q	1.029	0.029	0.000	0.000	0.000	0.000

Table 5.4. Power Flow Results with TCSC Controller

Power flow		Power at bus & Line flow			Line Loss	
From	To	MW	Mvar	MVA	MW	Mvar
1	7	0.73264	0.247	0.771	0.000	0.035
2	9	1.63	0.021	1.634	0.000	0.158
3	8	0.85	-0.125	0.858	0.000	0.043
4	7	-0.27	-0.39	0.489	0.0017	-0.164
	9	-0.98	-0.102	0.986	0.03	-0.256
5	7	-0.452	-0.128	0.473	0.00342	-0.143
	8	-0.451	-0.173	0.486	0.00771	-0.3474
6	9	-0.617	-0.142	0.632	0.00313	-0.129
	8	-0.389	-0.209	0.442	0.00186	-0.0207
7	1	-0.732	-0.211	0.768	0.000	0.035
	4	0.276	0.235	0.362	0.00172	-0.164
	5	0.451	-0.018	0.459	0.00342	-0.143
8	5	0.459	-0.163	0.489	0.00771	-0.344
	6	0.391	0.0005	0.394	0.00186	-0.207
	3	-0.85	0.016	0.866	0.000	0.043
9	4	1.01	-0.144	1.021	0.031	-0.256
	2	-1.63	0.137	1.631	0.000	0.158
	6	0.614	0.017	0.617	0.0031	-0.124
	Total loss				0.0488	-1.013

After performing load flow analysis on three machine nine bus system by Newton-Raphson Method the maximum power mismatch = 1.30589e-007 occured at fourth iteration. The magnitudes and phase angles of slack bus are obtained. The real and reactive powers of Generators and Loads are obtained and the real and reactive powers flowing in the lines i.e from one bus to other buses are obtained and the Line losses are calculated in all power transmission lines connected from one bus to another bus. Finally the total real power and reactive power losses are calculated. All these power flow in a line and losses in the lines and total loss are shown in the tabular 5.4.

5.4 Dynamic Modelling Of Three Machine Nine Bus System:

Here, we have considered the nine bus system as shown in Figure5.1 the above system has three generators, three load buses The modelling of the three machine nine bus system is done as per above single machine infinite bus system.

(i) Synchronous Machine Modelling

In this study, the three-machine nine-bus power system [23] shown in Fig.5.1 is considered. The generators are modelled in third order model [1], which consists of electro-mechanical swing equation, and q-axis generator internal voltage equation. The dynamic equations are shown from equations (1)-(3).

$$\dot{\delta}_i = \omega_i - \omega_0 \tag{5.3}$$

$$\dot{\omega}_i = -\frac{D_i}{M_i}\left[\omega_i - \omega_0\right] + \frac{\omega_0}{M_i}\left[P_{mi} - P_{ei}\right] \tag{5.4}$$

$$\dot{E}'_{qi} = \frac{1}{T'_{d0i}}\left[E_{fdi} - (X_{di} - X'_{di})\, I_{di} - E'_{qi}\right] \tag{5.5}$$

(ii) Exciter System Modelling

The conventional excitation system shown in Fig.5.2 is considered. It represents an automatic voltage regulator (AVR) and a power system stabilizer (PSS). The PSS transfer function consisting of PSS gain, wash-out and two stage lead-lag compensator. The wash-out acts as high pass filter, whereas the lead-lag compensator provides phase lead to compensate the phase lag between excitation and the generator electrical torque. The dynamic equation is given [1] by:

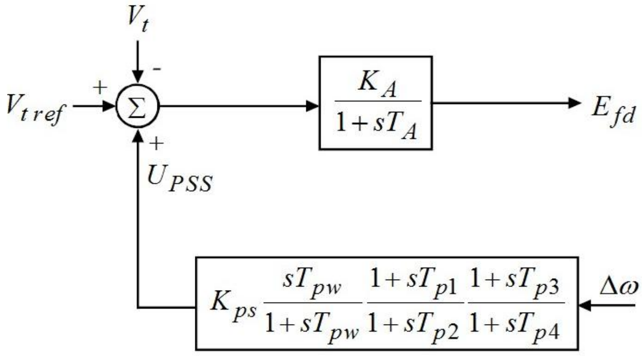


Fig.5. 2. Conventional excitation system with a PSS

$$\dot{E}_{fd} = \frac{1}{T_A}\left[K_A[V_{ref} - V_t + U_{PSS}] - E_{fd}\right] \tag{5.6}$$

Where Vref is the reference terminal voltage of the generator, K_A and T_A are the gain and time constant of the AVR. U_{PSS} is the output of conventional lead-lag based PSS.

(iii) TCSC Based Damping Controller

The TCSC damping controller can be modelled as a variable reactance for the load flow and dynamic stability studies. The controller structure of TCSC is shown in Fig.5.3. The dynamic equation for reactance of TCSC is given by

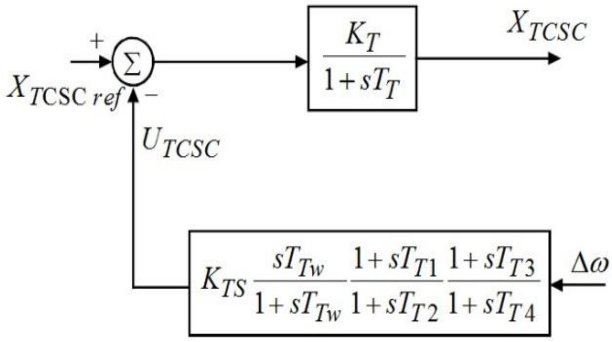


Fig.5.3. Structure of the TCSC damping controller

$$\dot{X}_{TCSC} = \frac{1}{T_T}\left[K_T(X_{TCSCref} - U_{TCSC}) - X_{TCSC}\right] \tag{5.7}$$

Where, $X_{TCSCref}$ is the reference reactance of TCSC, K_T and T_T are the gain and time constant of the TCSC. U_{TCSC} is the output of conventional lead-lag TCSC damping stabilizer.

5.4.1 Simultaneous coordinated design of PSS and TCSC damping controllers in Multi machine power system using PSO:

The proposed controller must be able to work well under all operating conditions, while the improvement for the damping of the critical modes is necessary. Since the selection of the

TCSC damping controller and PSS parameters is a complex optimization problem. Thus, to acquire an optimal combination and to improve the optimization synthesis and find the global optimum value an PSO algorithm has been employed [24]. A performance index based on the system dynamics after an impulse disturbance alternately occurs in the system is organized and used as the objective function for the design problem.

Objective function is a mathematical expression describing a relationship of the optimization parameters that uses the optimization parameters as inputs. In this paper, for optimization of coordinated damping controller parameters, integral of time-multiplied absolute value of error (ITAE) is considered as objective function. Since integral squired error (ISE) is considered only error and there is no importance is given to time. But for power system stability problems, it is required that settling time should be less and also oscillations should die out soon. However, the main objective is to damp the power oscillations and maintain the overall stability of the system [24]. This can be achieved by minimizing the value of speed deviations of generators. So the objective function is formulated with the integration of speed variation.The objective function is given by

$$J = \int_0^t t\ [\left|\omega_2 - \omega_1\right| + \left|\omega_3 - \omega_1\right|]\ dt \tag{5.8}$$

where t is total simulation time, ω_1, ω_2, and ω_3 are speeds of generators G_1, G_2, and G_3 respectively.

So the objective is to minimize '*J*' such that to satisfy the following inequality constraints,

$$K_S^{\min} \le K_S \le K_S^{\max} \tag{5.9}$$

$$T_1^{\min} \le T_1 \le T_1^{\max} \tag{5.10}$$

$$T_2^{\min} \le T_2 \le T_2^{\max} \tag{5.11}$$

$$T_3^{\min} \le T_3 \le T_3^{\max} \tag{5.12}$$

$$T_4^{\min} \le T_4 \le T_4^{\max} \tag{5.13}$$

where K_S represents gain of damping stabilizer block, and T_1,T_2,T_3,T_4 are the time constants of lead-lag blocks in the damping controllers. In this study, the coordinated controller parameters of PSS as well as TCSC damping controller is optimized based on the objective function given in Eq. (13) using Particle Swarm Optimization Technique(PSO) described in chapter 4. The flow chart of PSO algorithm based coordinated design of PSS with TCSC damping controller is depicted in previous Fig. 4.4. With this coordination of damping controllers in multi machine system using PSO we can damp out low frequency oscillations very effectively and we can attain the transient stability very quickly.

CHAPTER 6

Simulation Results and Discussion

6.1 Dynamic Performance of SMIB System with PSS and TCSC:

The power system stabilizer (PSS) and thyristor controlled series compensator (TCSC) are employed in single machine infinite bus system to damp out low frequency oscillations occurred in the system when severe disturbance taken place at any one of the transmission lines. The employment of these controllers will improve the transient stability of in single machine infinite bus system. In this chapter we will go through the results of single machine infinite bus system equipped with PSS and TCSC damping controllers without coordination and with coordination using particle swarm optimization. Similarly we will go through the results coordination of PSS and TCSC damping controllers in Three machine Nine bus multi machine power system using particle swarm optimization.

The close-loop behaviour of the system with different control schemes is simulated using MATLAB programming. A three phase fault is applied at one of the transmission line is considered for analysis of SMIB system with TCSC. The performance of the system is analyzed under following different loading conditions:

a) Nominal loading: P_e=1.0p.u. and Q_e=0.25p.u.

b) Heavy loading: P_e=1.2p.u. and Q_e=0.35p.u.

c) Lightly loading: P_e= 0.8p.u. and Q_e=0.15p.u.

The fault that we consider here is a symmetrical three-phase short circuit fault on one of the parallel lines at a point which is very nearer to the generator bus bar, occurs at a time t=1sec, and it is cleared at t=1.1sec (i.e. the fault is applied for 6 cycles).Here frequency considered is 60 Hz. The results of time responses computed with the alternative controllers for nominal loading, heavy loading and lightly loading respectively are shown in Fig. 6.1 to 6.3. The responses of rotor angle variation, rotor speed variation are shown in figures 6.1(a) and 6.1(b) respectively.

6.1(a) Nominal Loading (P_e=1.0p.u. and Q_e=0.25p.u.)

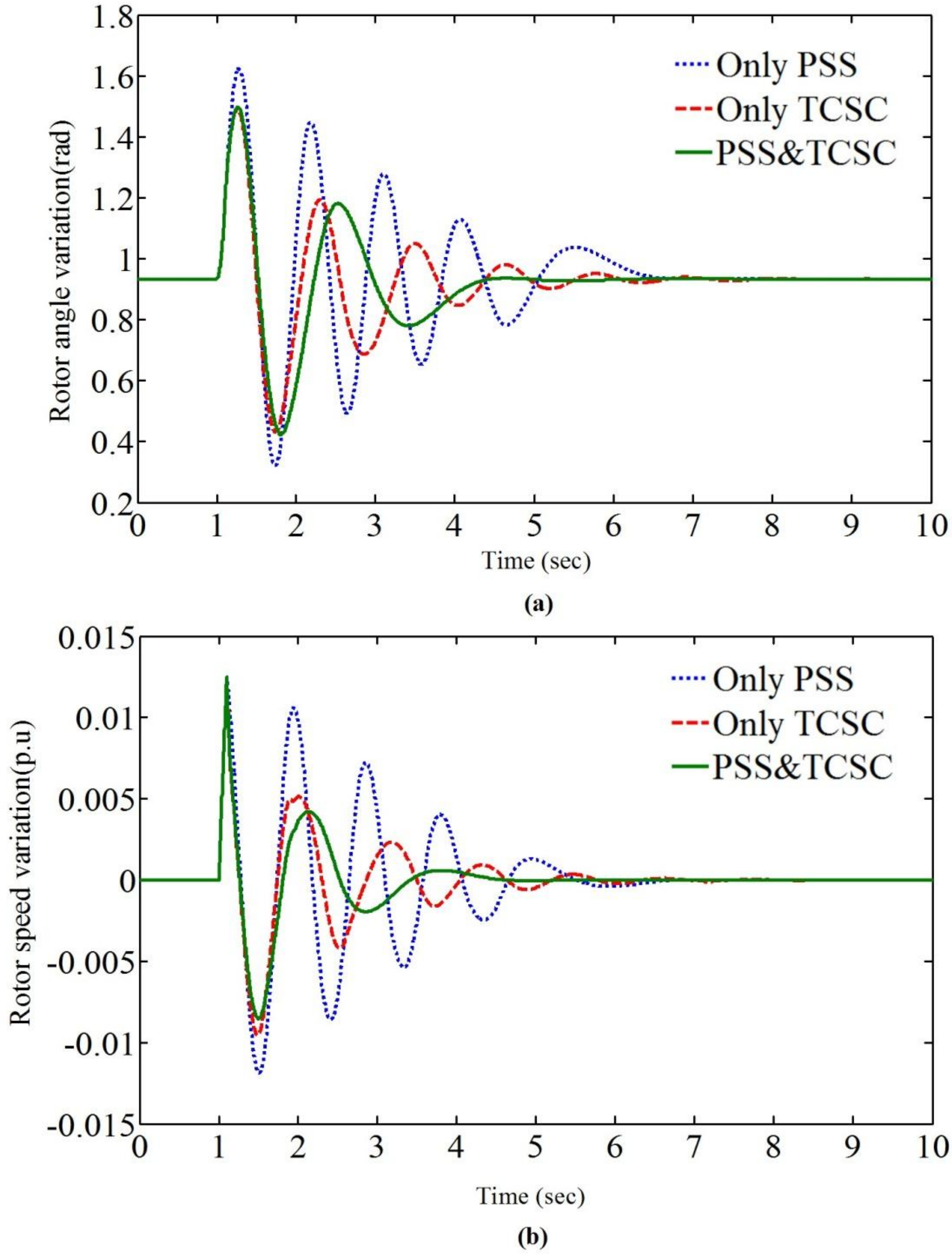


Fig.6.1 System dynamic response for a six cycle fault disturbance with Nominal Loading condition. (a) Rotor angle variation (b) Rotor speed variation

6.1(b) Heavy Loading (P_e=1.2p.u. and Q_e=0.35p.u)

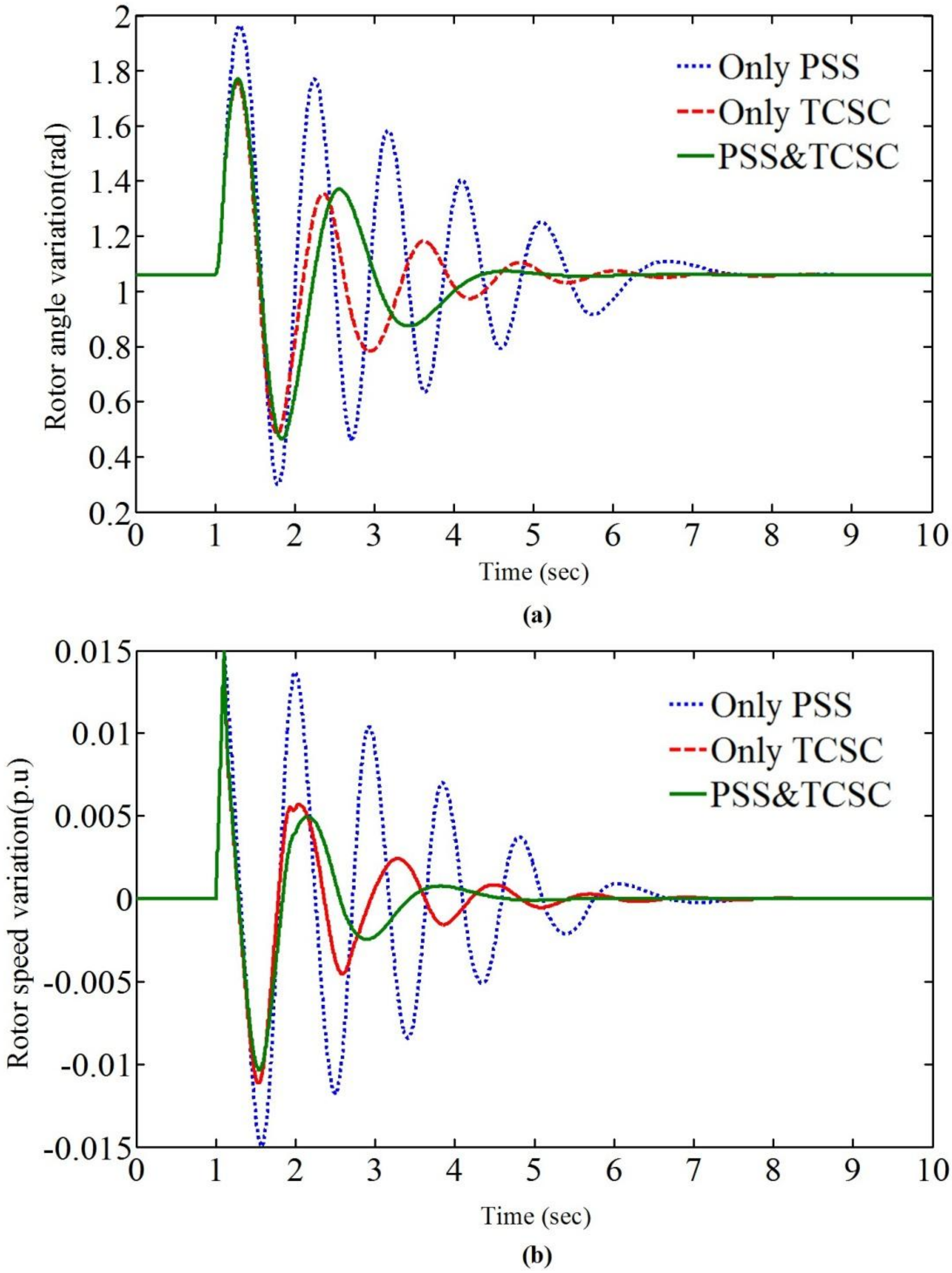
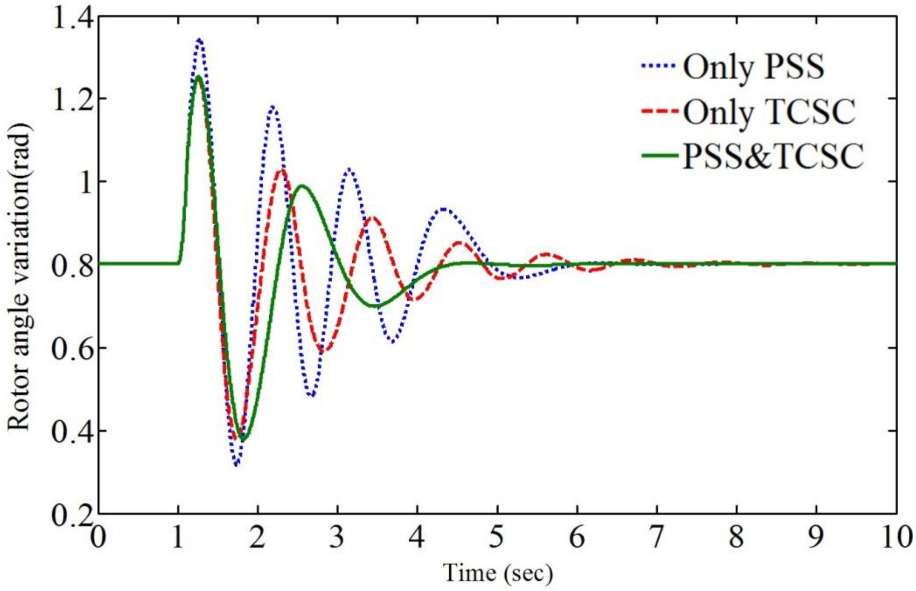
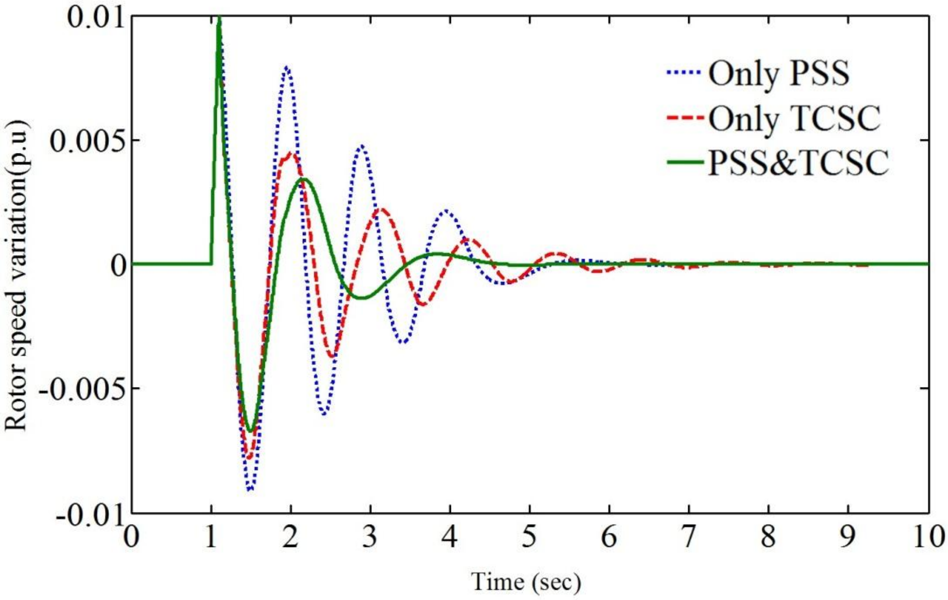


Fig.6.2 System dynamic response for a six cycle fault disturbance with Heavy Loading condition. (a) Rotor angle variation (b) Rotor speed variation

6.1(c) Lightly Loading (P_e= 0.8p.u. and Q_e=0.15p.u.)



(a)



(b)

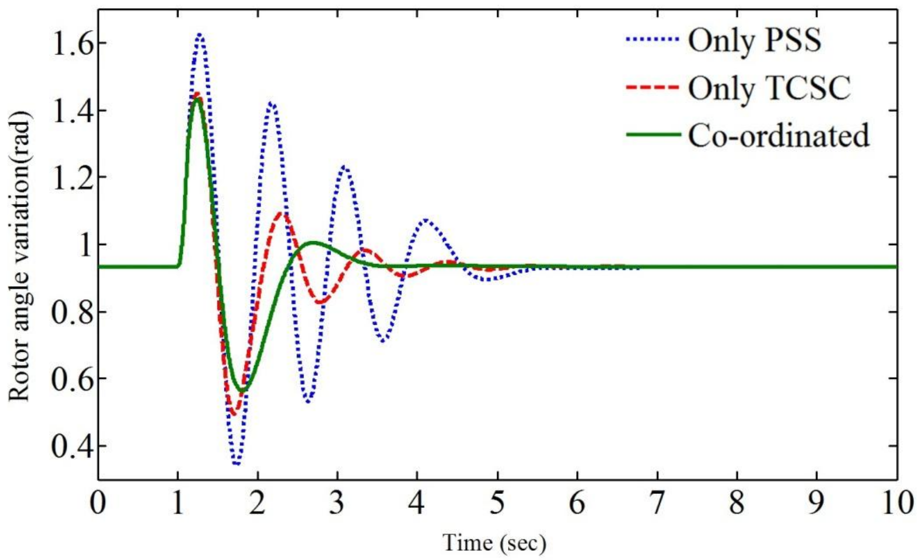
Fig.6.3 System dynamic response for a six cycle fault disturbance with Light Loading condition. (a) Rotor angle variation (b) Rotor speed variation

Discussion:

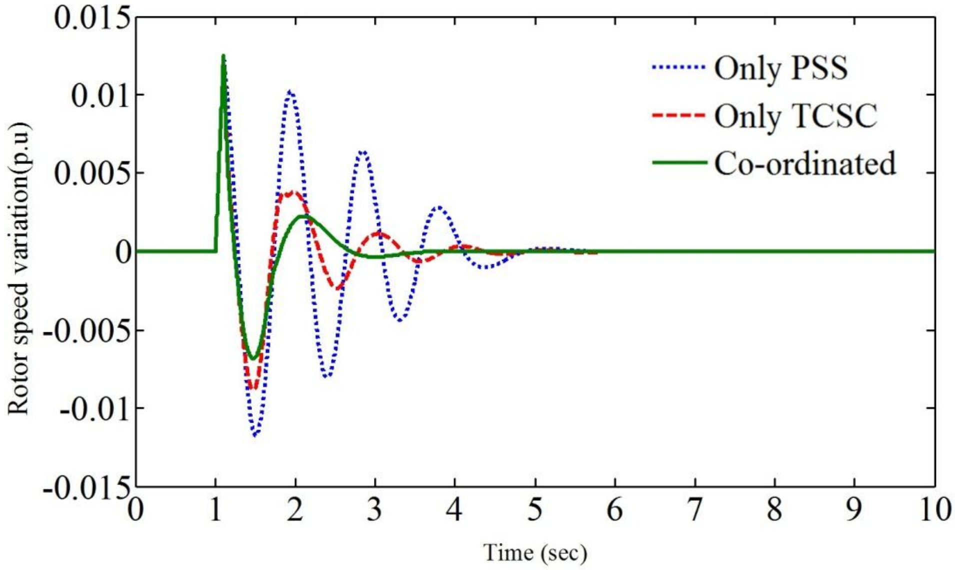
The simulation results show that the system employed with PSS&TCSC controllers provides good damping characteristics to low frequency oscillations quickly stabilizes the system under a disturbance when compared with only PSS and only TCSC Controllers.

6.2 Dynamic Performance of SMIB System with PSS and TCSC damping controllers Coordinated using Particle Swarm Optimization (PSO):

6.2(a) Nominal Loading (P_e=1.0p.u. and Q_e=0.25p.u.)



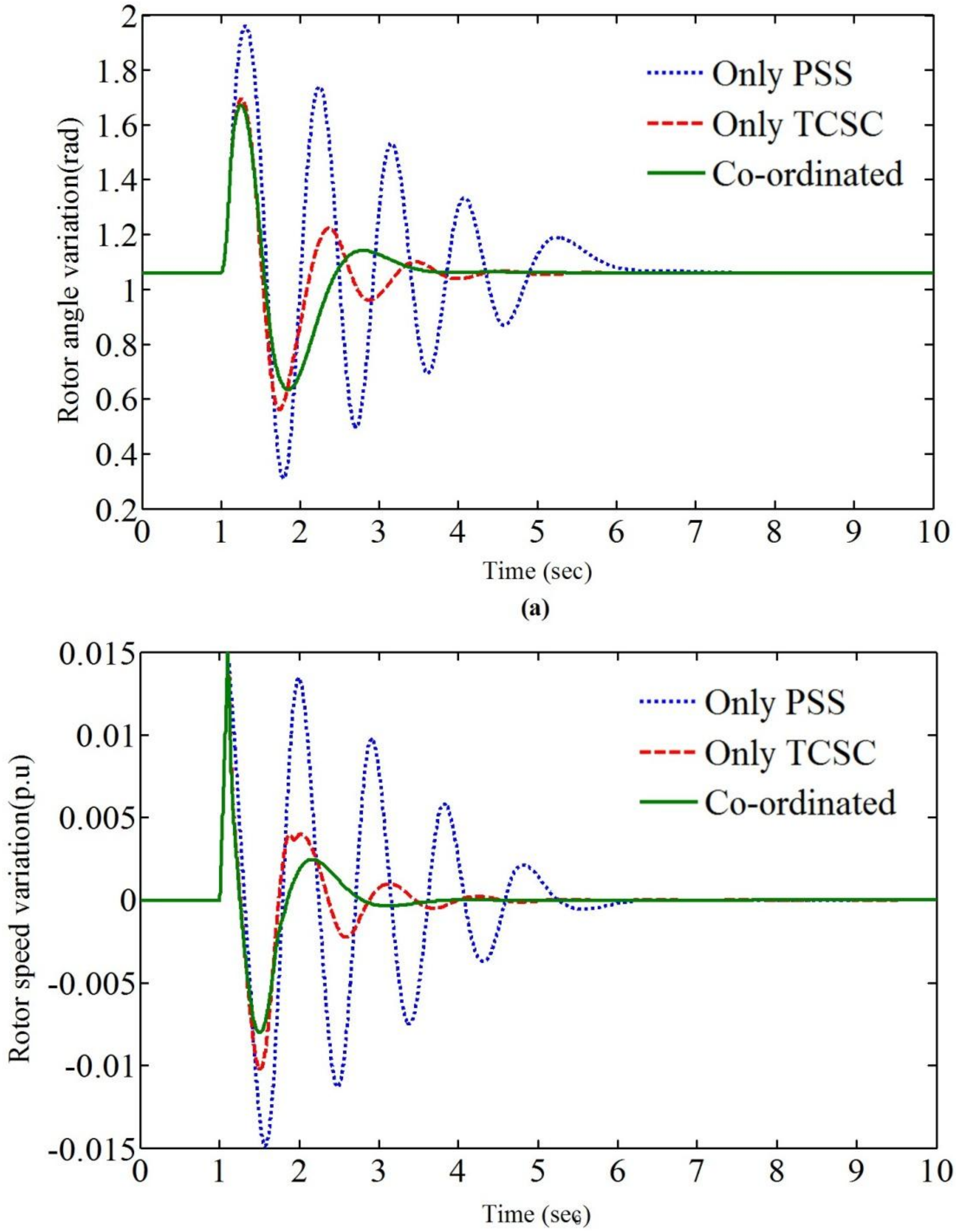
(a)



(b)

Fig.6.4 System dynamic response for a six cycle fault disturbance with nominal loading condition. (a) Rotor angle variation (b) Rotor speed variation

6.2 (b) Heavy Loading (P_e=1.2p.u. and Q_e=0.35p.u)

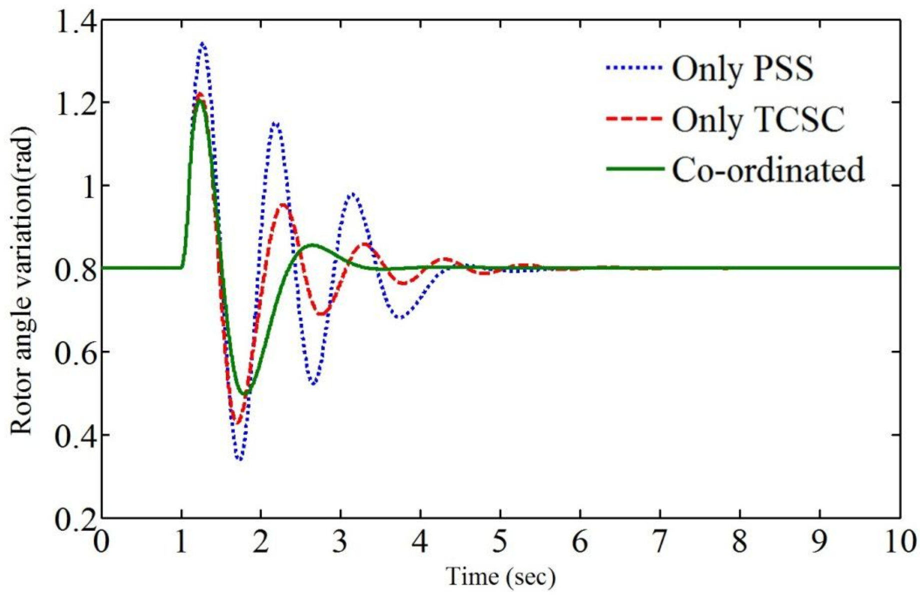


(a)

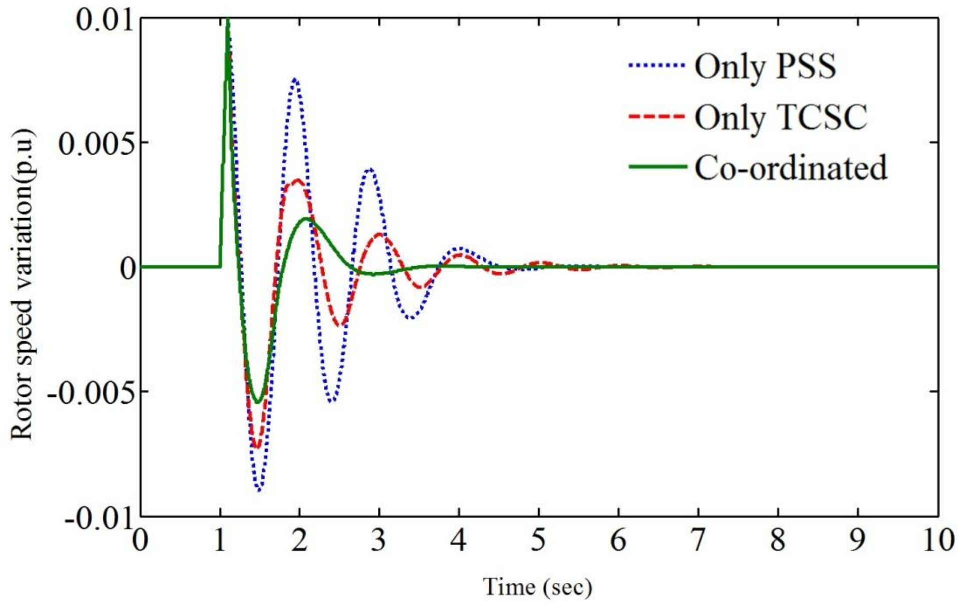
(b)

Fig.6.5 System dynamic response for a six cycle fault disturbance with heavy loading condition. (a) Rotor angle variation (b) Rotor speed variation

6.2 (c) Lightly Loading (P_e= 0.8p.u. and Q_e=0.15p.u.)



(a)



(b)

Fig.6.6 System dynamic response for a six cycle fault disturbance with light loading condition. (a) Rotor angle variation (b) Rotor speed variation

Discussion:

The above simulation results of 6.4 to 6.6 (a),(b) show that the system employed with coordinated PSS and TCSC controllers provides good damping characteristics to low frequency oscillations quickly stabilizes the system under a disturbance when compared with only PSS and only TCSC Controllers but when compared with results of Fig. 6.1 to 6.3 (a),(b) this Fig. 6.4 to 6.6 (a),(b) results provides good damping characteristics to low frequency oscillations quickly stabilizes the system under a disturbance. Hence we can conclude that the system with proper coordination of damping controllers provides good damping characteristics and it attains transient stability quickly. We also conclude that if the fault clearing time is less, more stability improvement. On the other hand less transient stability improvement occurs if fault clearing time is more.

6.3 Dynamic Performance of a Three Machine, Nine Bus System with PSS and TCSC damping controllers Coordinated using Particle Swarm Optimization:

In this analysis the three-machine nine-bus system is considered. The PSSs installed at generators G2, G3 and a simple exciter installed at generator G1. The power flow in line 4-9 is the largest in the test system and this line is the longest line too. Hence, the best location to install TCSC is in series with the line 4-9 is considered in this study. The dynamic performance of the test system is analyzed under different loading conditions given in table 6.1. The non-linear model simulation is carried out using MATLAB programming for a three phase fault. The fault is applied at bus 9 and cleared by tripping the line 9-6 permanently. The fault applied at 1 sec. and cleared at 1.1sec (i.e. a six cycle fault is applied to the system).

TABLE 6.1

TEST SYSTEM DIFFERENT LOADING CONDITIONS

	Nominal loading		**Heavy loading**		**Lightly loading**	
	P	**Q**	**P**	**Q**	**P**	**Q**
Generator						
G_1	0.7326	0.2436	0.8320	0.6178	0.5278	-0.3088
G_2	1.6300	0.0215	2.4450	0.4248	0.8150	-0.2431
G_3	0.8500	-0.1217	1.2750	0.1373	0.4250	-0.2343
Load						
A	1.25	0.50	1.90	0.75	0.65	0.25
B	0.90	0.30	1.30	0.45	0.45	0.15
C	1.00	0.35	1.50	0.50	0.50	0.17

6.3(a). Nominal Loading Condition

The effectiveness of proposed coordinated controller is tested with the test system under nominal loading. The Fig.6.7 (a),(b),(c),(d) represents the rotor angle change of Generator 2 and Generator 3 with respect to Generator 1 and rotor speed change of Generator 2 and Generator 3 with respect to Generator 1.The oscillations are not damped in case of system without controller due to the large disturbance. Whereas the coordinated controller shows better damping effect to power oscillations when compare with individual controllers. The settling time of these oscillations are also very good for the system having coordinated controller

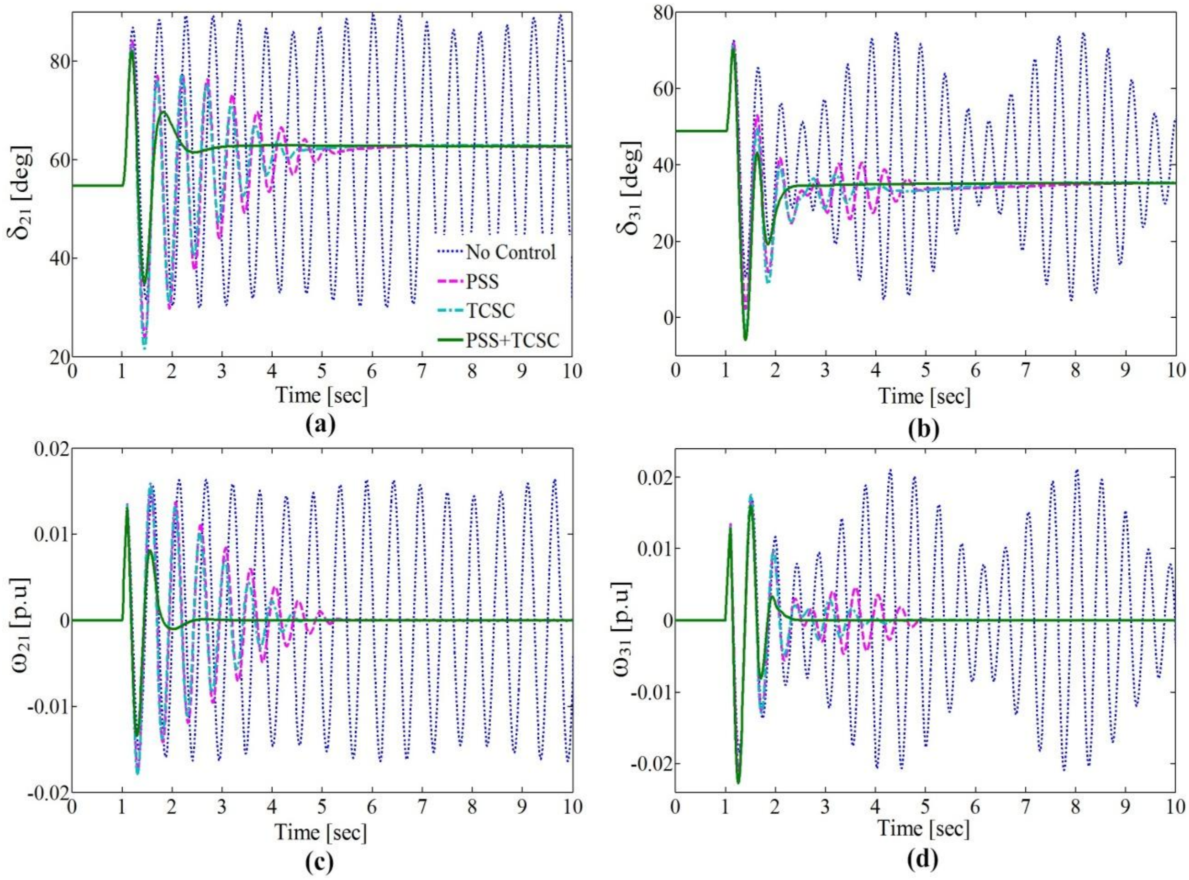


Fig.6.7. System dynamic response for Nominal loading (a)Rotor angle change of δ_{21}(b) Rotor angle change of δ_{31}(c) Rotor speed change of ω_{21}(d) Rotor speed change of ω_{31}

6.3(b). Heavy Loading Condition

To test the robustness of proposed coordinated controller the test system is operated even in heavy loading condition. The Fig.6.8(a),(b),(c),(d) represents the rotor angle change of Generator 2 and Generator 3 with respect to Generator 1 and rotor speed change of Generator 2 and Generator 3 with respect to Generator 1.From the results the test system without any controller unstable and the generators are loses their synchronism. However the test system with coordinated controller shows better damping as well as adequate settling time compared with individual controllers. In heavy loading condition also the proposed controller performs well in all accepts.

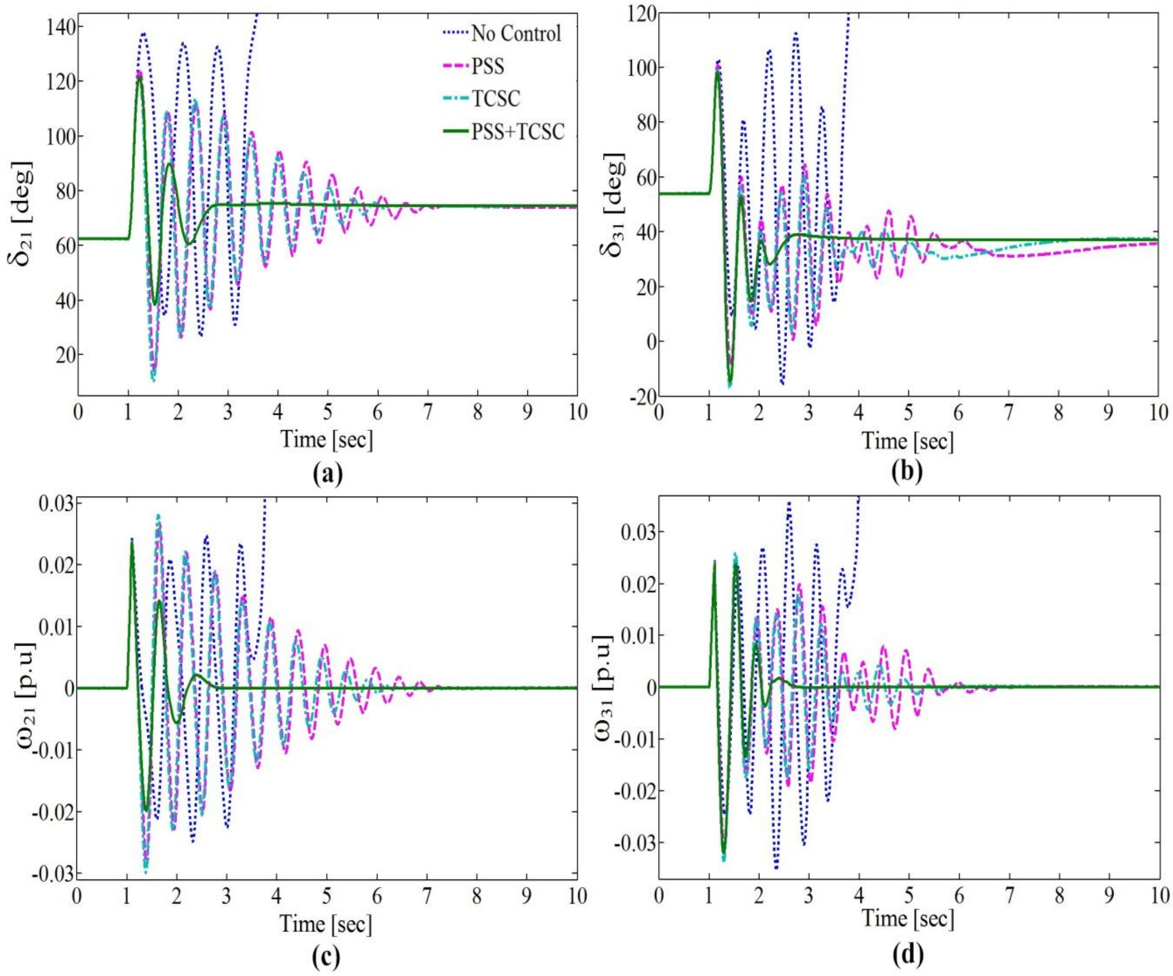


Fig.6.8.System dynamic response for Heavy loading (a) Rotor angle change of δ_{21}(b) Rotor angle change of δ_{31}(c) Rotor speed change of ω_{21}(d) Rotor speed change of ω_{31}

6.3(c).Lightly Loading Condition:

The Fig.6.7(a),(b),(c),(d) represents the rotor angle change of Generator 2 and Generator 3 with respect to Generator 1 and rotor speed change of Generator 2 and Generator 3 with respect to Generator 1. In lightly loading condition the power oscillations are large in magnitude. The power oscillations damp out quickly with the proposed coordinated controller compared with other controller schemes. However the test system with no controller unable to damp out the oscillations. Hence, the robustness of proposed coordinated damping controller tested in three different loading conditions. It gives acceptable damping effect and adequate settling time for power oscillations under severe disturbance.

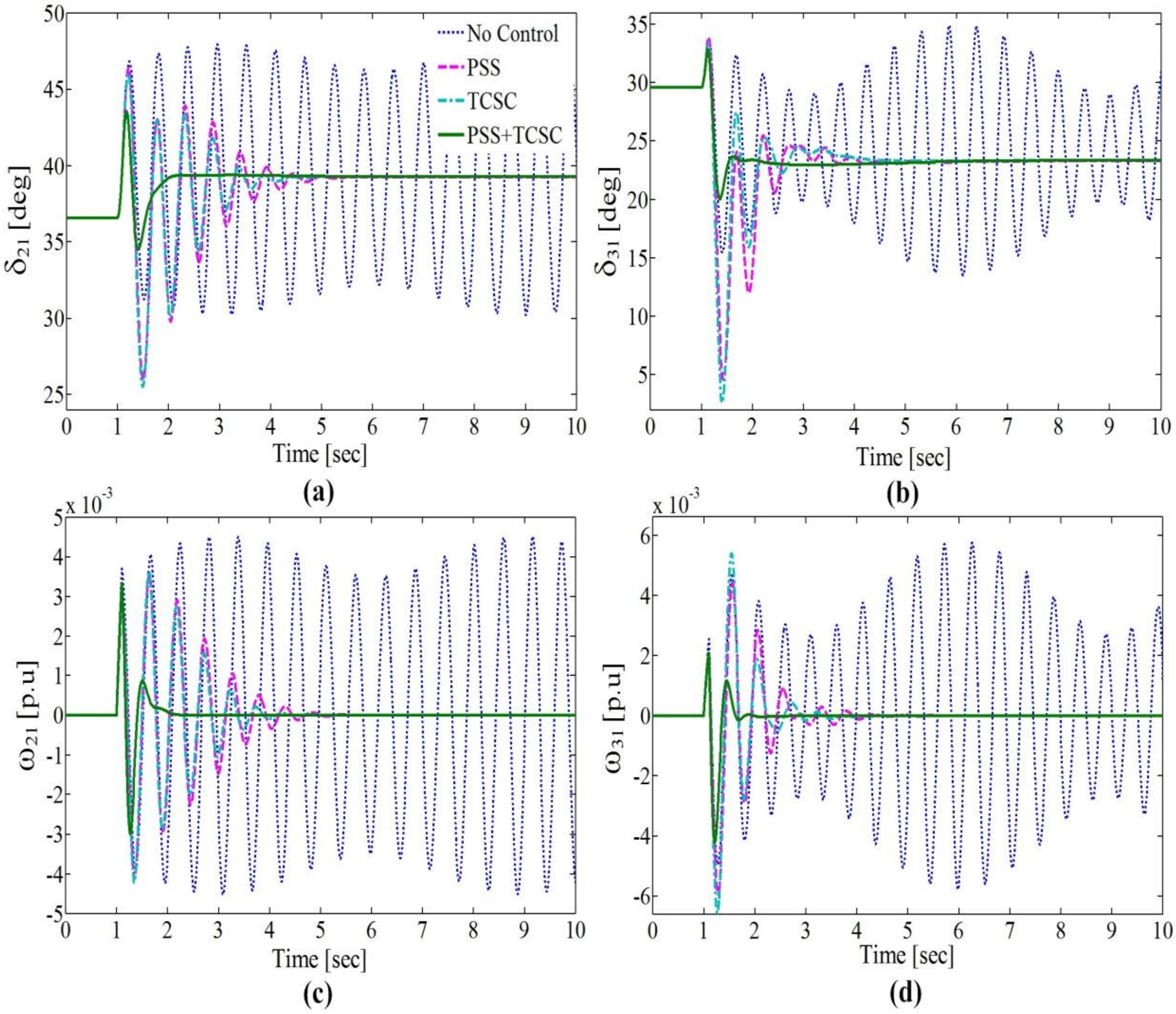


Fig.6.9 System dynamic response for Lightly loading (a)Rotor angle change of δ_{21} (b) Rotor angle change of δ_{31} (c) Rotor speed change of ω_{21} (d) Rotor speed change of ω_{31}

Discussion:

The above simulation results of three machine nine bus system show that the system employed with coordinated PSS and TCSC controllers provides good damping characteristics to low frequency oscillations quickly stabilizes the system under a disturbance when compared with system without control and with only PSS damping control and with only TCSC damping control. Hence we can conclude that the system with proper coordination of damping controllers provides good damping characteristics and it attains transient stability quickly. We also conclude that if the fault clearing time is less, it will attain transient stability very quickly. On the other hand if fault clearing time is more it will take more time to attain transient stability.

CHAPTER 7

CONCLUSIONS & SCOPE OF FUTURE WORK

7.1 CONCLUSIONS:

In this Report, An optimized coordinated control of a power system stabilizer (PSS) with TCSC based damping controller is discussed. An objective function is minimized using PSO for finding the optimal control parameters of coordinated controller. Different control schemes are employed on the test system to investigate the performance of the proposed controller. The time domain simulation of a non-linear system is carried out in MATLAB software package. The robustness of the proposed coordinated controller is investigated by testing its performance under different loading conditions. The simulation results show that the test system dynamic performance and overall damping effect are enhanced by simultaneous tuning of PSS and TCSC damping controllers. Therefore, coordinated control of PSS and TCSC based damping controller provides better damping of power oscillations.

7.2 SCOPE OF FUTURE WORK:

- We can extend the same co-ordination technique for Large Multi machine system (16 machine 68 bus power systems).
- The coordinated controller can be validated in Real-Time using RTDS.
- The control parameters of coordinated controller are optimized using advanced optimization techniques.

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[1] **Sunil Kumar Sunkara**, P.C.Panda and Rajendraprasad Narne, "Coordinated Tuning of PSS with TCSC Damping Controller through Advanced Adaptive PSO for a Multi-machine Power System" IEEE International Conference on Energy Efficient Technologies for Sustainability (ICEETS'13).